Hierarchical RL and Skill Discovery

CS 224R

Reminders

Today:	Project milestone due
Wednesday next week:	Homework 4 due

The Plan

Information-theoretic concepts

Skill discovery

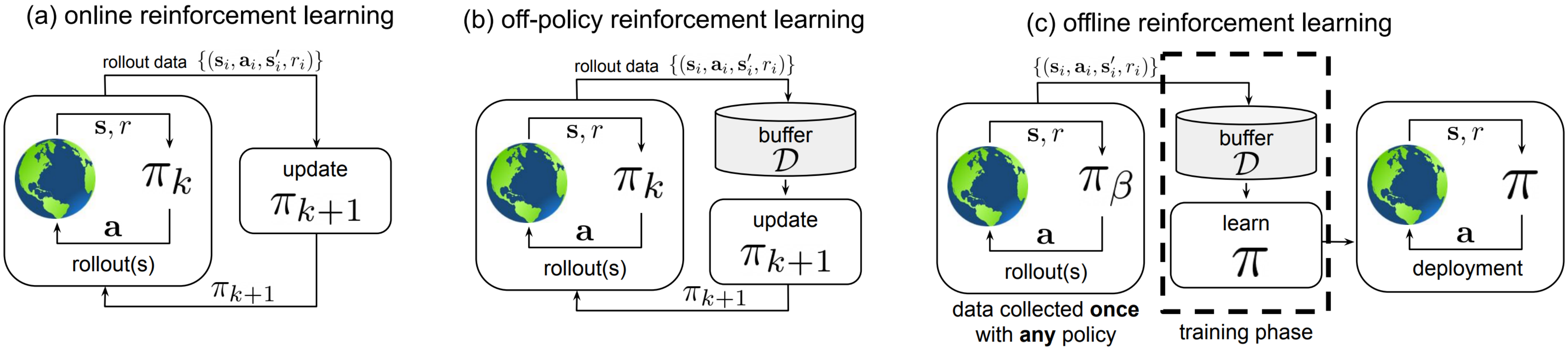
Using discovered skills

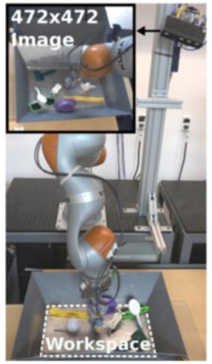
Hierarchical RL

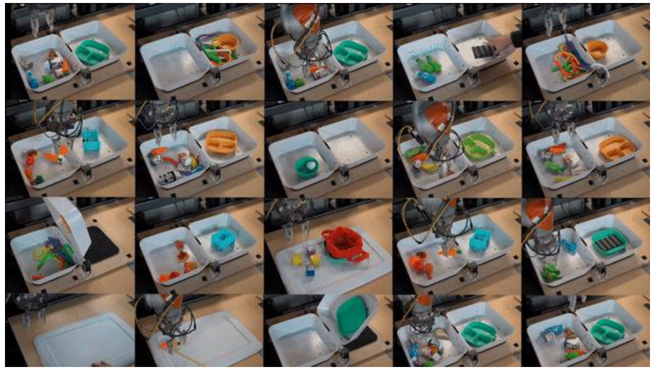
Key learning goals:

- Understand the concept of a skill and basic algorithms in this space
- Overview of hierarchical RL algorithms

Recall: RL so far







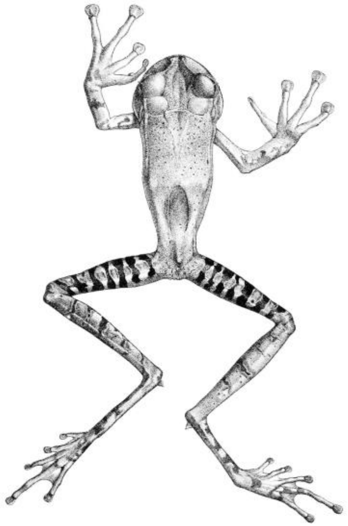
We knew what we wanted

Short-horizon behaviors

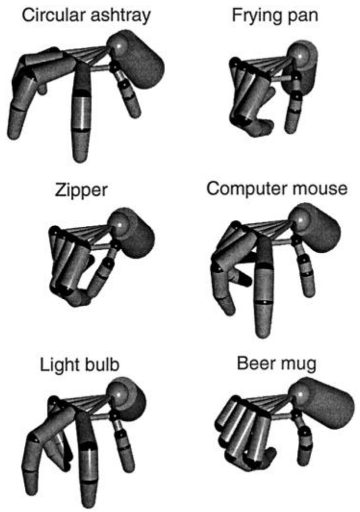
Well defined tasks/rewards

Why Skill Discovery?

What if we want to discover interesting behaviors?



[The construction of movement by the spinal cord, *Tresch et al.*, 1999]

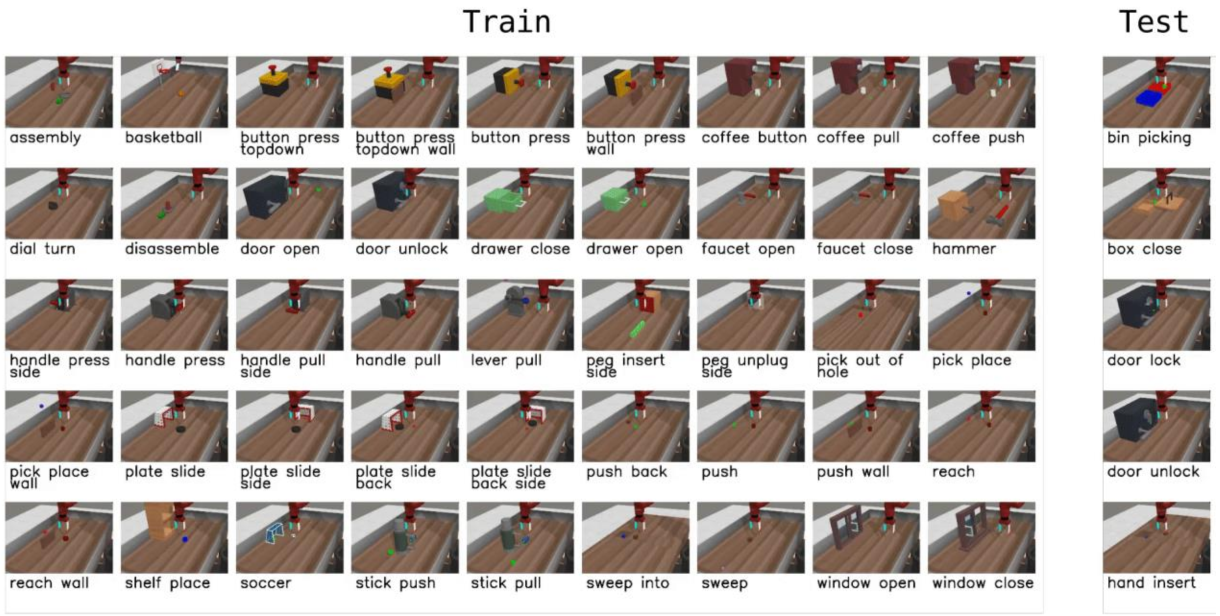


[Postural hand synergies for tool use, *Santello, et al.*, 1998]

Why Skill Discovery? More practical version

Coming up with tasks is tricky…

Task ideas for a tabletop manipulation scenario



[Meta-World, *Yu, Quillen, He, Julian, et al.*, 2019]

Why Hierarchical RL?

Performing tasks at various levels of abstractions

Bake a cheesecake

Buy ingredients

Go to the store

Walk to the door

Take a step

Contract muscle X

Exploration

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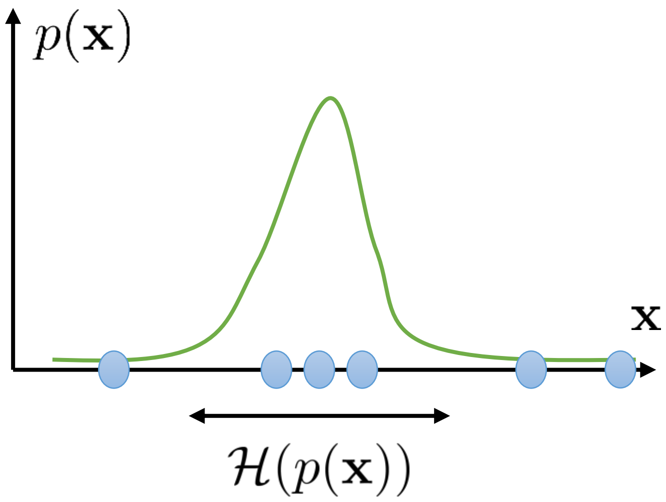
Hierarchical RL

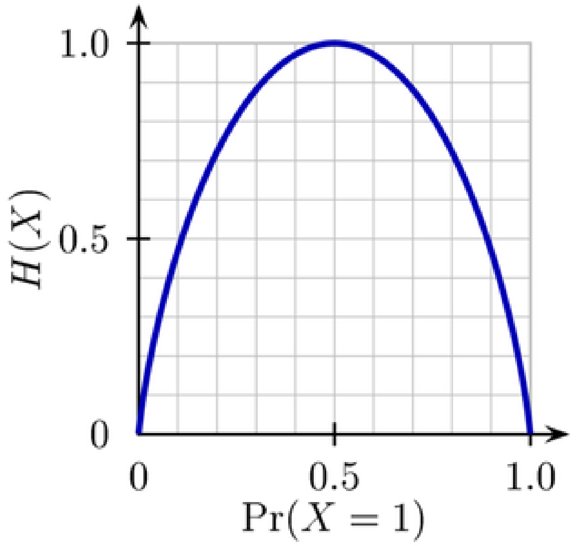
Entropy

$p(\mathbf{x})$ distribution (e.g., over observations $\mathbf{x}$)



$$\mathcal{H}(p(\mathbf{x})) = -E_{\mathbf{x}\sim p(\mathbf{x})}[\log p(\mathbf{x})]$$

entropy – how "broad" $p(\mathbf{x})$ is

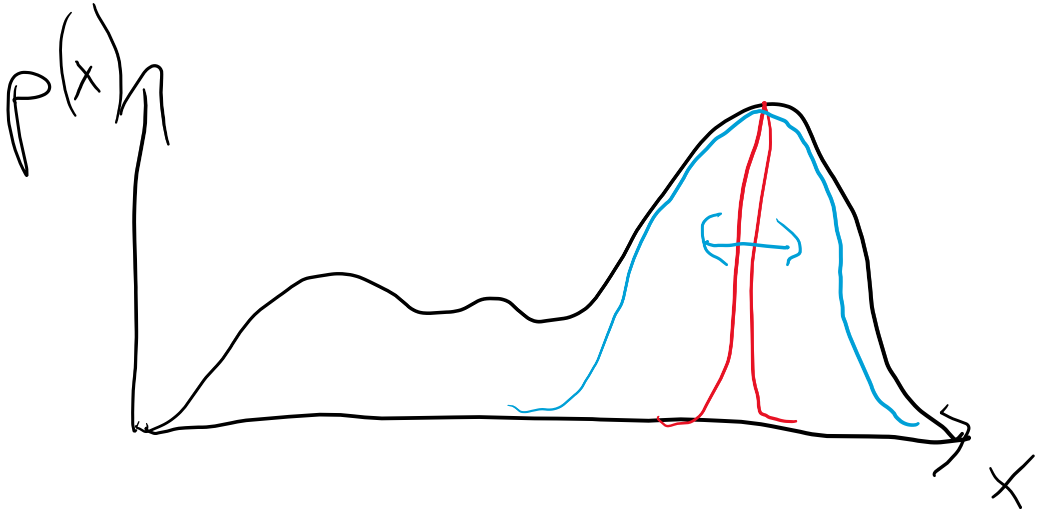


Slide adapted from Sergey Levine

KL-divergence

Distance between two distributions

$$\mathbb{D}_{KL}(q||p) = \mathbb{E}_q\left[\log\frac{q(x)}{p(x)}\right] = \mathbb{E}_q \log q(x) - \mathbb{E}_q \log p(x) = -\mathbb{E}_q \log p(x) - \mathcal{H}(q(x))$$

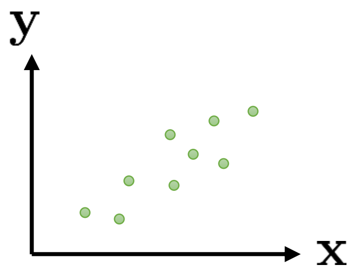


Mutual information

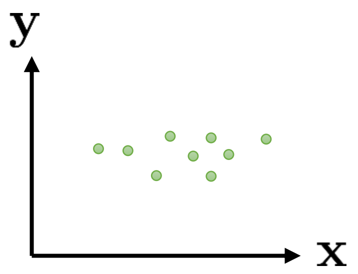
$$\mathcal{I}(\mathbf{x};\mathbf{y}) = D_{\mathrm{KL}}(p(\mathbf{x},\mathbf{y})\|p(\mathbf{x})p(\mathbf{y}))$$

$$= E_{(\mathbf{x},\mathbf{y})\sim p(\mathbf{x},\mathbf{y})}\left[\log \frac{p(\mathbf{x},\mathbf{y})}{p(\mathbf{x})p(\mathbf{y})}\right]$$

$$= \mathcal{H}(p(\mathbf{y})) - \mathcal{H}(p(\mathbf{y}|\mathbf{x})) = \mathcal{H}(p(\mathbf{x})) - \mathcal{H}(p(\mathbf{x}|\mathbf{y}))$$



high MI: $\mathbf{x}$ and $\mathbf{y}$ are *dependent*



low MI: $\mathbf{x}$ and $\mathbf{y}$ are *independent*

High MI?

x- it rains tomorrow, y – streets are wet tomorrow

x- it rains tomorrow, y – we find life on Mars tomorrow

Mutual information

$$\mathcal{I}(\mathbf{x};\mathbf{y}) = D_{\mathrm{KL}}(p(\mathbf{x},\mathbf{y})\|p(\mathbf{x})p(\mathbf{y}))$$

$$= E_{(\mathbf{x},\mathbf{y})\sim p(\mathbf{x},\mathbf{y})}\left[\log \frac{p(\mathbf{x},\mathbf{y})}{p(\mathbf{x})p(\mathbf{y})}\right]$$

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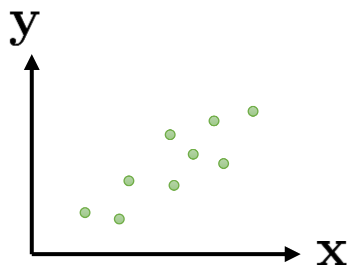
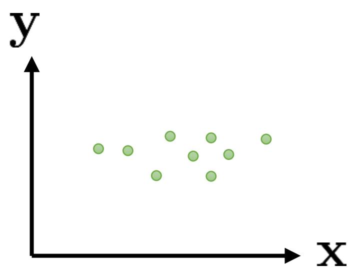


high MI: $\mathbf{x}$ and $\mathbf{y}$ are *dependent*



low MI: $\mathbf{x}$ and $\mathbf{y}$ are *independent*

example of mutual information: "empowerment" (Polani et al.)

$$\mathcal{I}(\mathbf{s}_{t+1};\mathbf{a}_t) = \mathcal{H}(\mathbf{s}_{t+1}) - \mathcal{H}(\mathbf{s}_{t+1}|\mathbf{a}_t)$$

Slide adapted from Sergey Levine

The Plan

Information-theoretic concepts

Skill discovery

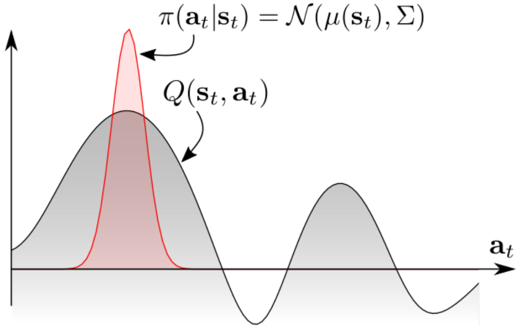
Using discovered skills

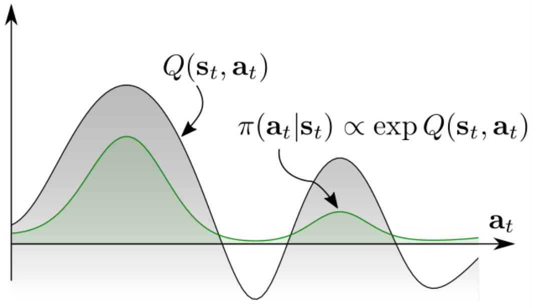
Hierarchical RL

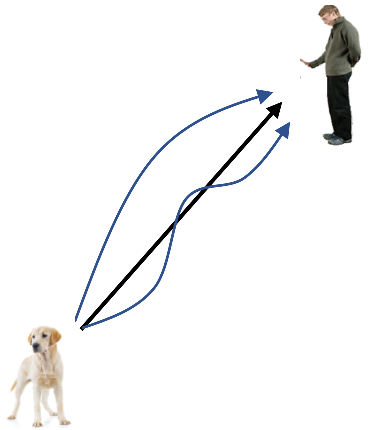
Soft Q-learning

Objective:

$$\sum_t E_{(\mathbf{s}_t,\mathbf{a}_t)\sim q}\left[r(\mathbf{s}_t,\mathbf{a}_t)+\mathcal{H}(q(\mathbf{a}_t|\mathbf{s}_t))\right]$$







Q-learning

1. collect dataset $\{(\mathbf{s}_i,\mathbf{a}_i,\mathbf{s}'_i,r_i)\}$

$K\times$

2. set $\mathbf{y}_i \leftarrow r(\mathbf{s}_i,\mathbf{a}_i)+\gamma\max_{\mathbf{a}'_i}Q_\phi(\mathbf{s}'_i,\mathbf{a}'_i)$
3. set $\phi \leftarrow \arg\min_\phi \frac{1}{2}\sum_i \|Q_\phi(\mathbf{s}_i,\mathbf{a}_i)-\mathbf{y}_i\|^2$

$$\pi(\mathbf{a}|\mathbf{s})=\underset{\mathbf{a}}{\mathrm{arg}max}Q_\phi(\mathbf{s},\mathbf{a})$$

Soft Q-learning

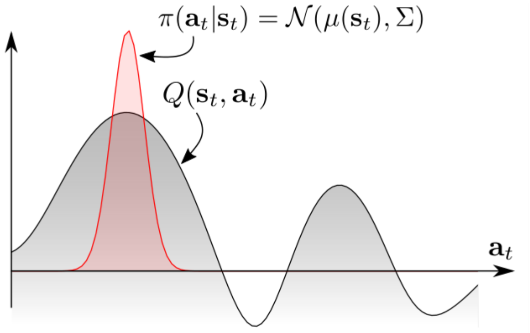
1. collect dataset $\{(\mathbf{s}_i,\mathbf{a}_i,\mathbf{s}'_i,r_i)\}$

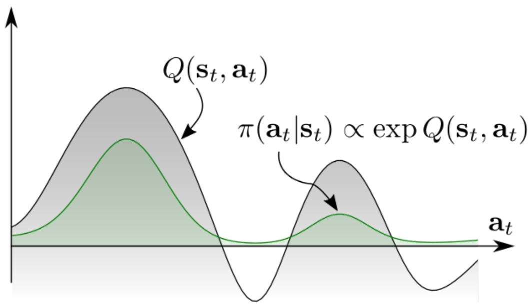
$K\times$

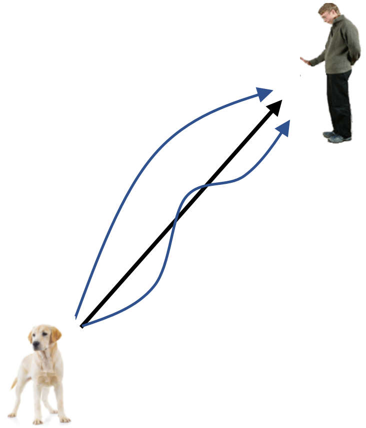
2. set $\mathbf{y}_i \leftarrow r(\mathbf{s}_i,\mathbf{a}_i)+\gamma\overset{\text{softmax}}{\cancel{\max}}_{\mathbf{a}'_i}Q_\phi(\mathbf{s}'_i,\mathbf{a}'_i)$
3. set $\phi \leftarrow \arg\min_\phi \frac{1}{2}\sum_i \|Q_\phi(\mathbf{s}_i,\mathbf{a}_i)-\mathbf{y}_i\|^2$

$$\pi(\mathbf{a}|\mathbf{s})=\mathrm{arg}\cancel{\underset{\mathbf{a}}{max}Q_\phi(\mathbf{s},\mathbf{a})}\propto\exp(A_t(s_t,a_t))$$

Soft Q-learning



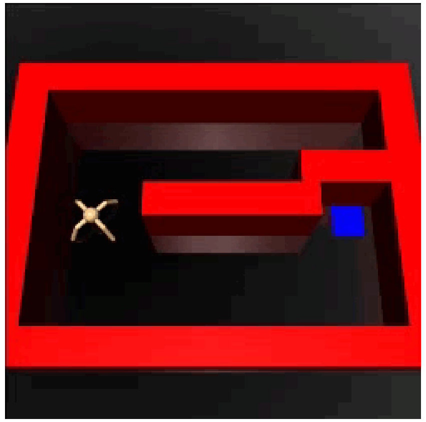


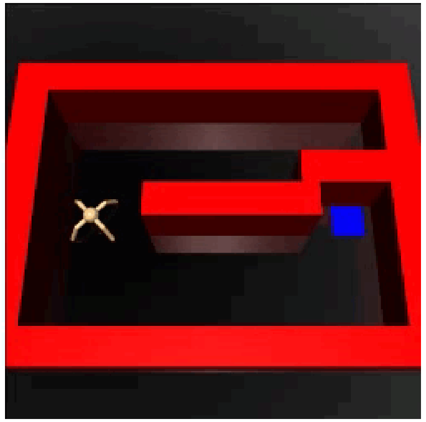


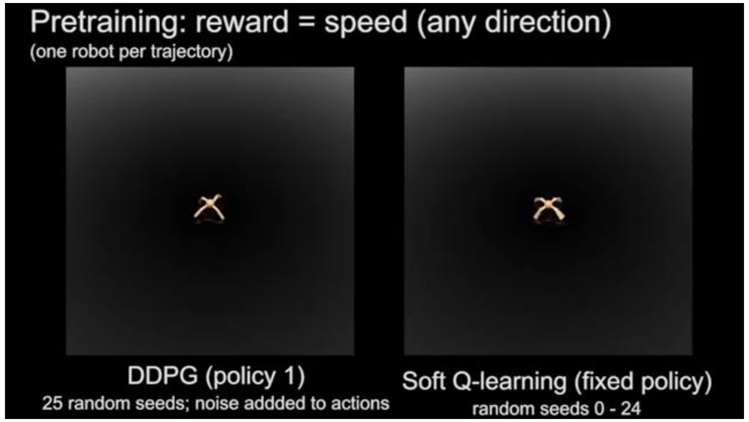
Exploration

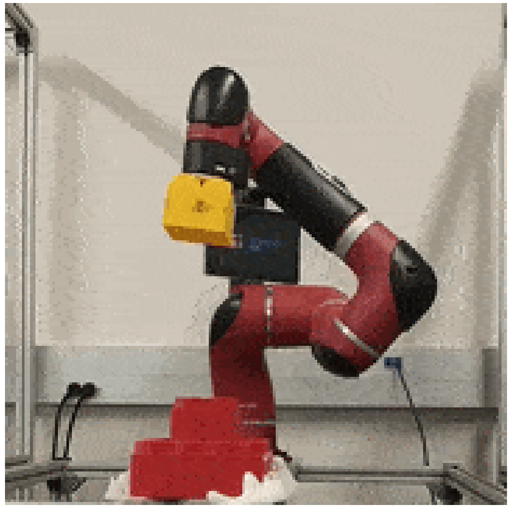
Fine-tunability

Robustness







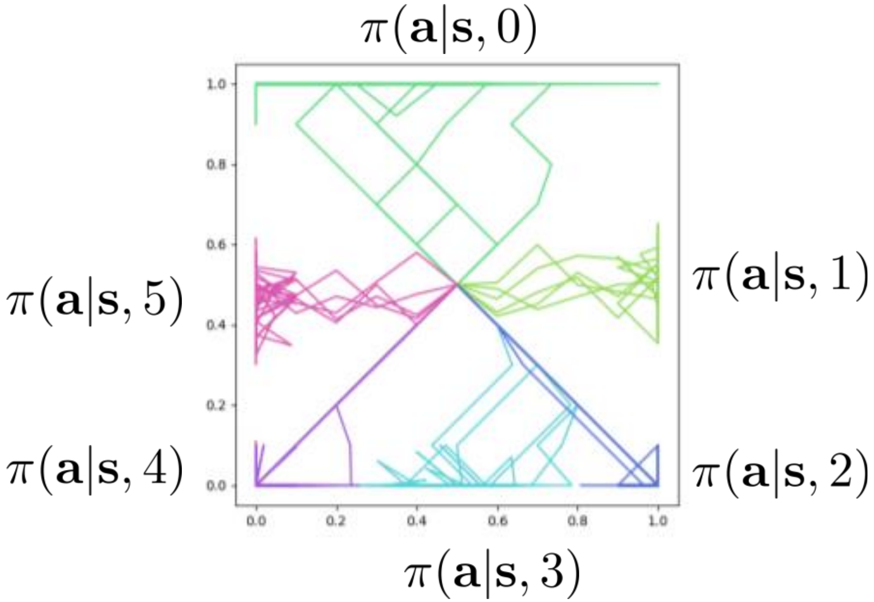


Haarnoja et al. RL with Deep Energy-Based Policies, 2017

Learning diverse skills

$$\pi(\mathbf{a}|\mathbf{s}, z)$$

task index



Why can't we just use MaxEnt RL

1. **action** entropy is not the same as **state** entropy

   agent can take very different actions, but land in similar states

2. MaxEnt policies are stochastic, but not always **controllable**

   intuitively, we want **low** diversity for a fixed *z*, high diversity *across z's*

Intuition: different **skills** should visit different **state-space regions**

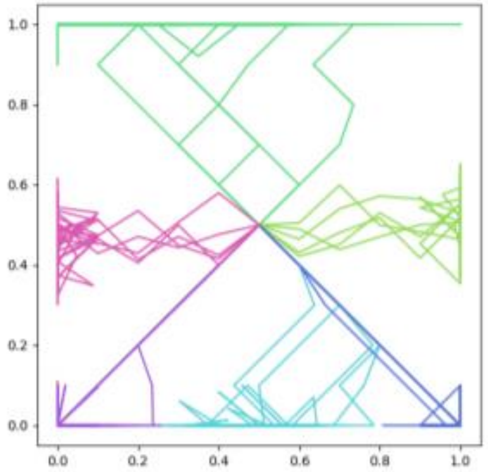
Eysenbach, Gupta, Ibarz, Levine. **Diversity is All You Need.**

Slide adapted from Sergey Levine

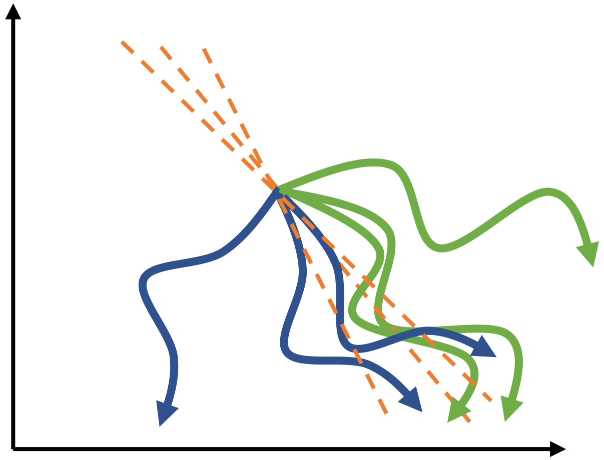
Diversity-promoting reward function

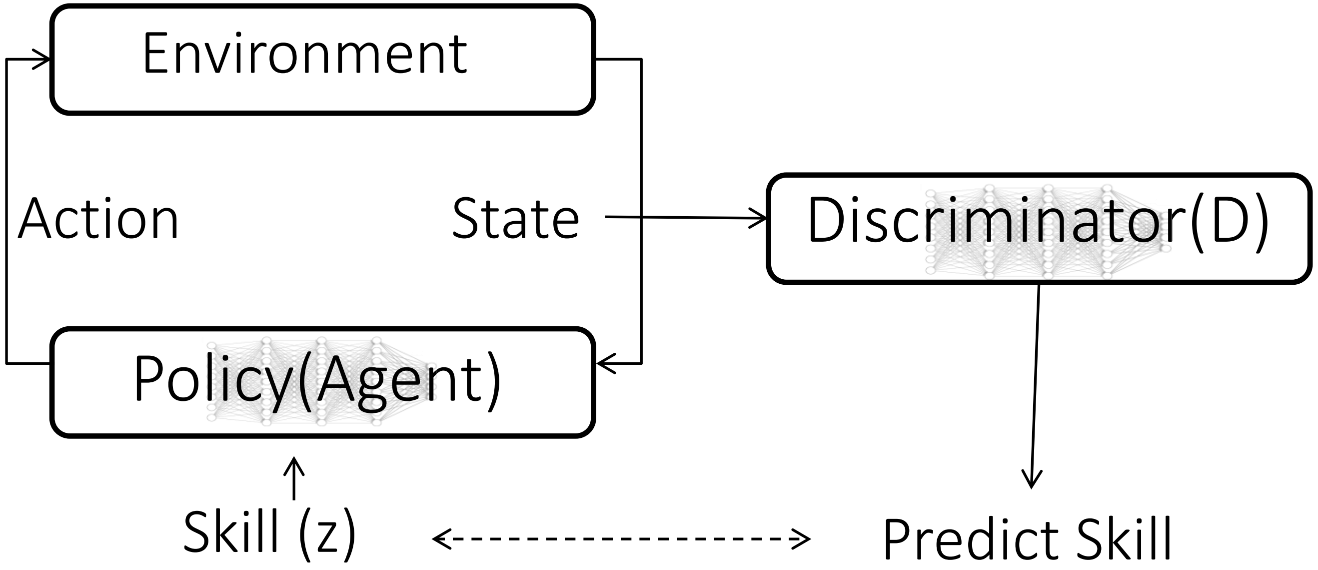
$$\pi(\mathbf{a}|\mathbf{s}, z) = \arg\max_{\pi} \sum_{z} E_{\mathbf{s}\sim\pi(\mathbf{s}|z)}[r(\mathbf{s}, z)]$$

reward states that are unlikely for other $z' \neq z$



$$r(\mathbf{s}, z) = \log p(z|\mathbf{s})$$

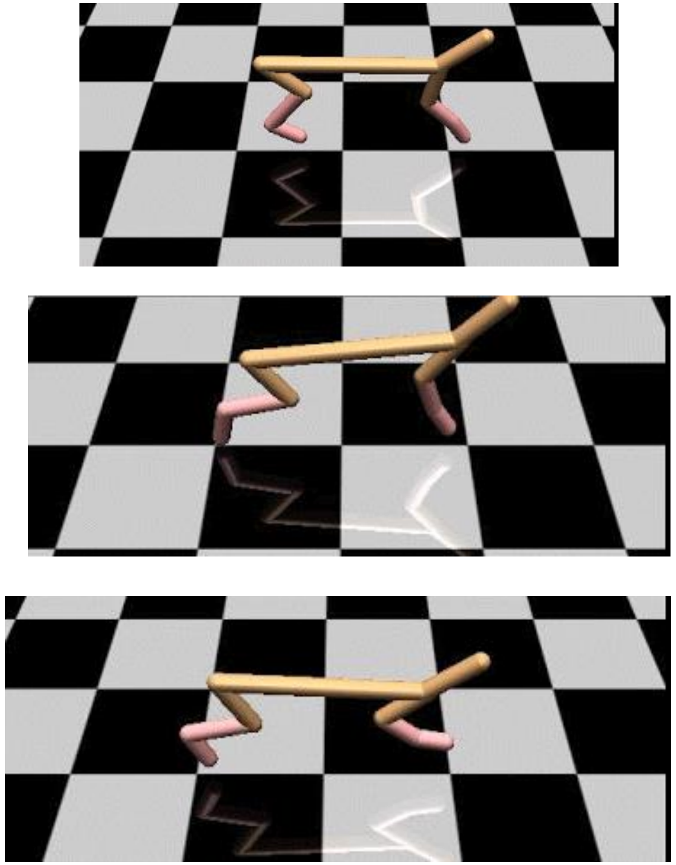




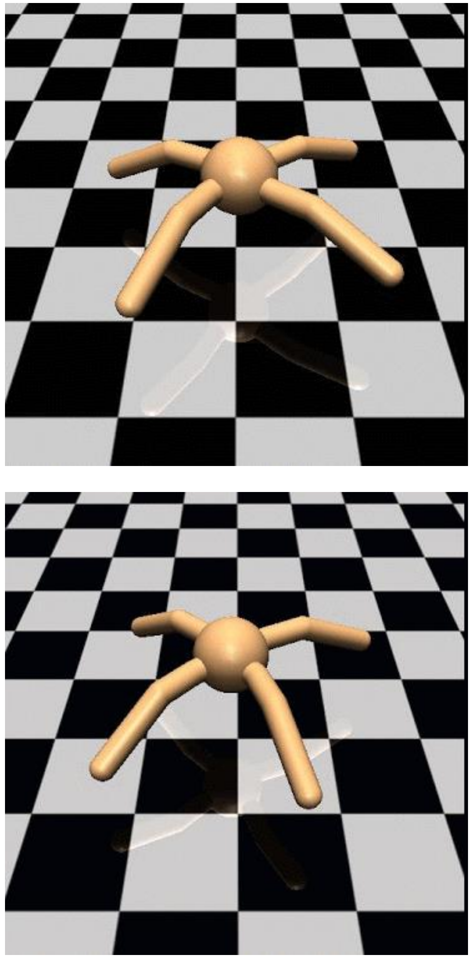
Eysenbach, Gupta, Ibarz, Levine. **Diversity is All You Need.**

Slide adapted from Sergey Levine

Examples of learned tasks



Cheetah



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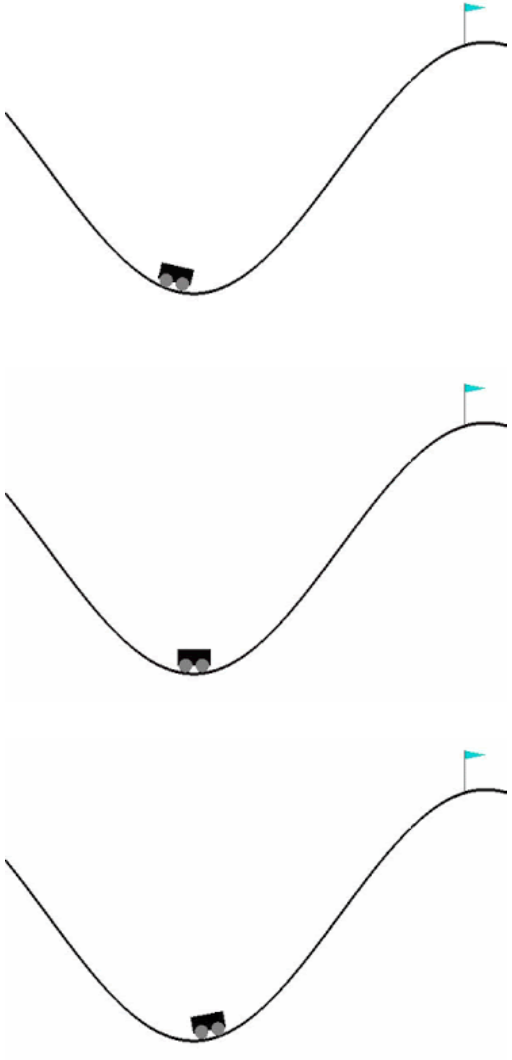


Mountain car

Eysenbach, Gupta, Ibarz, Levine. **Diversity is All You Need.**

A connection to mutual information

$$\pi(\mathbf{a}|\mathbf{s}, z) = \arg\max_{\pi} \sum_{z} E_{\mathbf{s}\sim\pi(\mathbf{s}|z)}[r(\mathbf{s}, z)]$$

$$r(\mathbf{s}, z) = \log p(z|\mathbf{s})$$

$$I(z, \mathbf{s}) = H(z) - H(z|s)$$

maximized by using uniform prior $p(z)$

minimized by maximizing $\log p(z|\mathbf{s})$

Eysenbach, Gupta, Ibarz, Levine. **Diversity is All You Need.**

See also: Gregor et al. **Variational Intrinsic Control.** 2016

Slide adapted from Sergey Levine

The Plan

Information-theoretic concepts

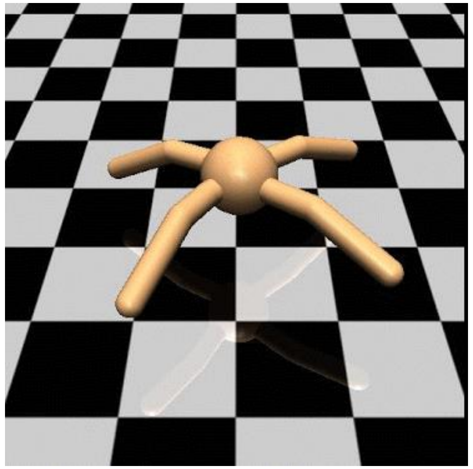
Skill discovery

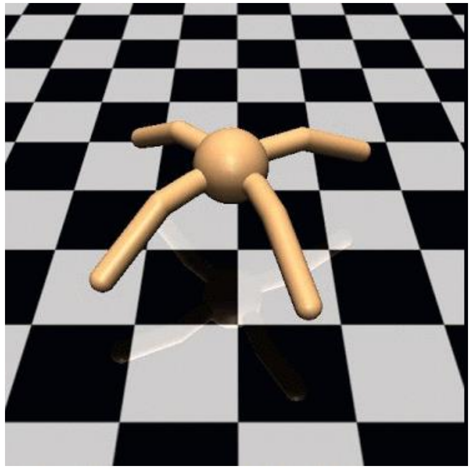
Using discovered skills

Hierarchical RL

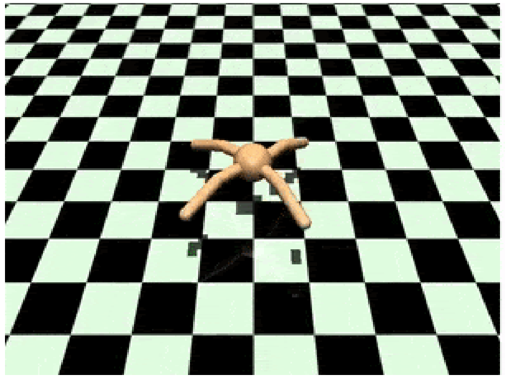
How to use learned skills?

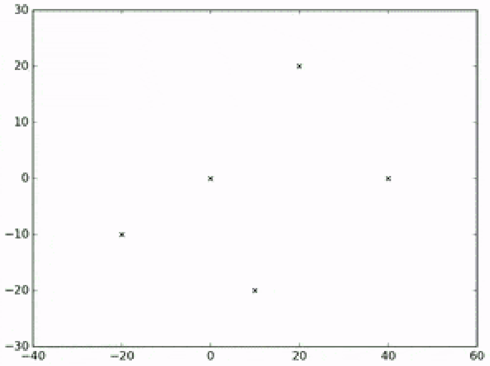
$$\pi(\mathbf{a}|\mathbf{s}, z)$$





How can we use the learned skills to accomplish a task?

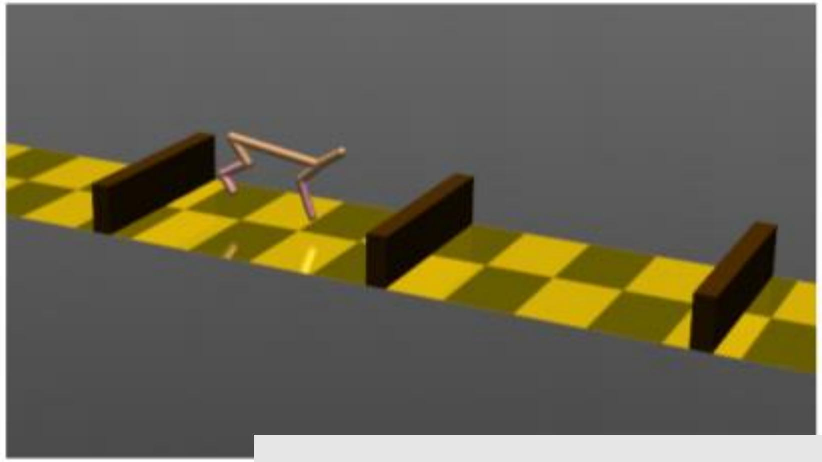


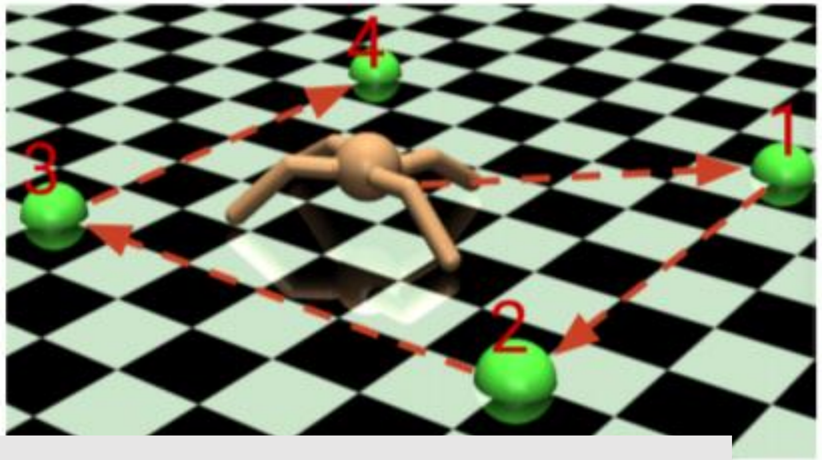


Learn a policy that operates on z's

Eysenbach, Gupta, Ibarz, Levine. **Diversity is All You Need.**

Results: hierarchical RL





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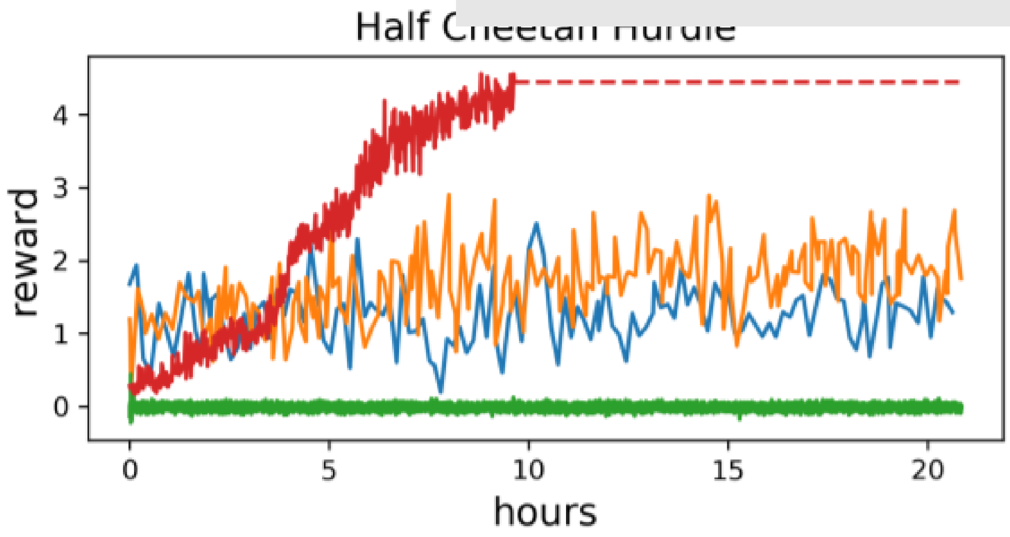
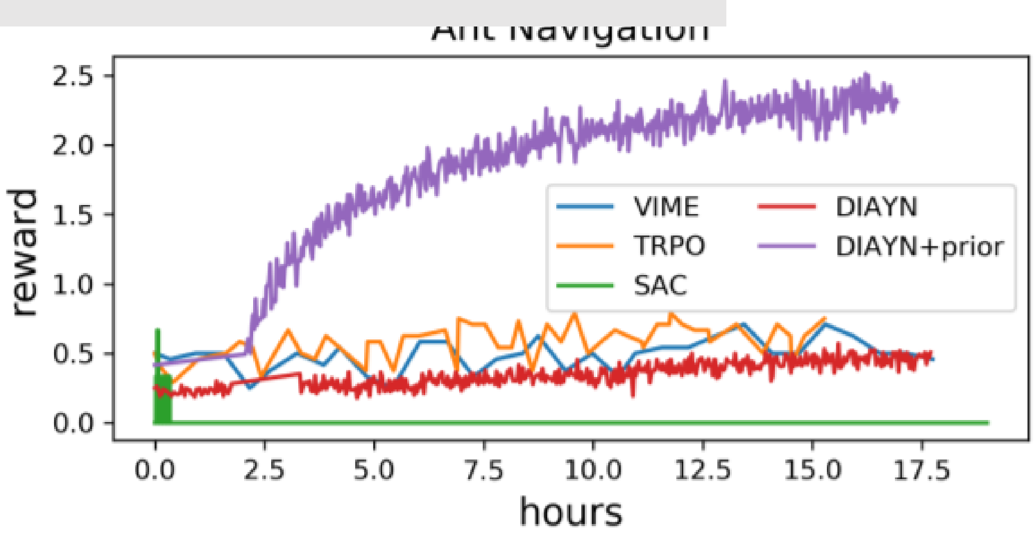
Can we do better?

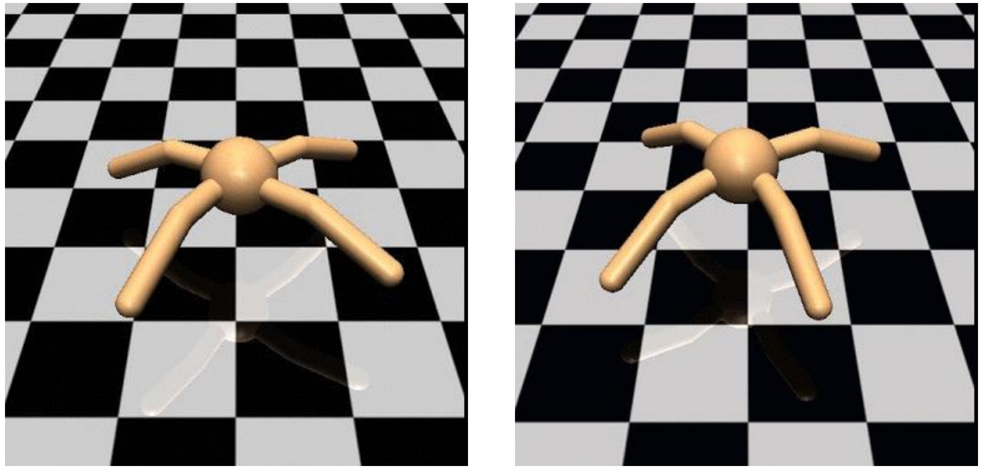




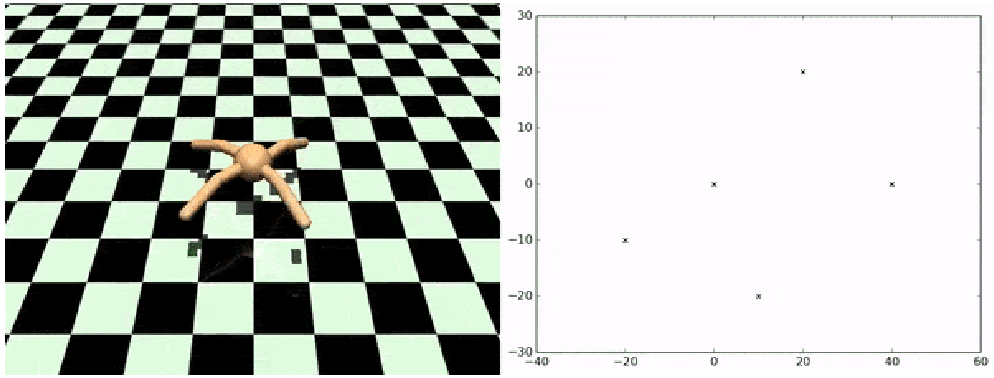
Eysenbach, Gupta, Ibarz, Levine. **Diversity is All You Need.**

What’s the problem?

Skills might not be particularly useful



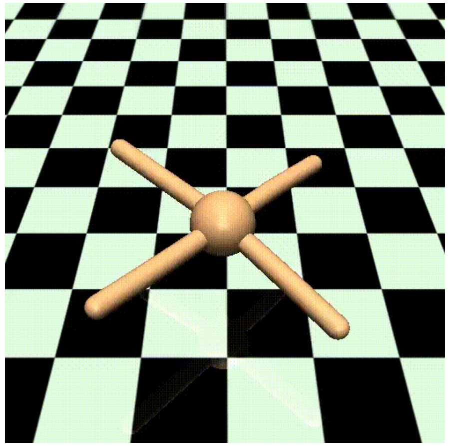
It’s not very easy to use the learned skills

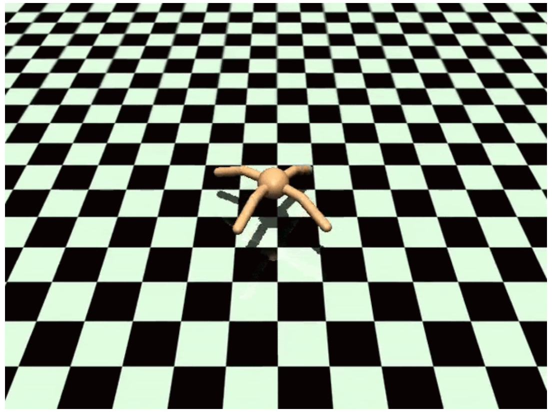


What makes a useful skill?

What’s the problem?

Consequences
are **hard** to
predict





Consequences
are **easy** to
predict

Slightly different mutual information

$$I(z, \mathbf{s}) = H(z) - H(z|s)$$

$$\max \mathcal{I}(s', z \mid s) = \max \left(\mathcal{H}(s' \mid s) - \mathcal{H}(s' \mid s, z) \right)$$

$I(x, y | z)$ $p(x, y | z)$ $p(x | z)$ $p(y | z)$

$$\mathcal{I}(\mathbf{x}; \mathbf{y}) = D_{\mathrm{KL}}(p(\mathbf{x}, \mathbf{y}) \| p(\mathbf{x}) p(\mathbf{y}))$$

Future hard to predict for different skills

Predictable future for a given skill

$$I(s'; z|s) \geq \mathbb{E}_s \mathbb{E}_z \mathbb{E}_{p(s'|s,z)} [\log \frac{q_\phi(s'|s, z)}{p(s'|s)}]$$

$$\approx \mathbb{E}_s \mathbb{E}_z \mathbb{E}_{p(s'|s,z)} [\log \frac{q_\phi(s'|s, z)}{\sum_{i=1}^{L} q_\phi(s'|s, z_i)} + \log L]$$

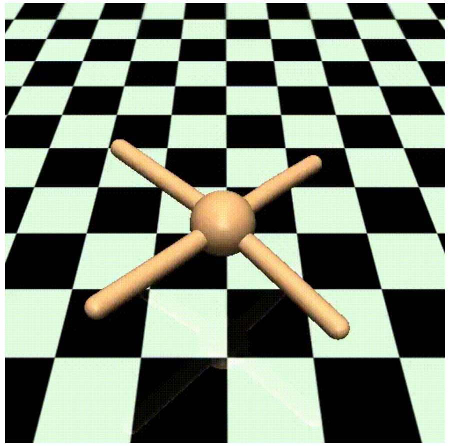
Sharma, Gu, Levine, Kumar, Hausman, **DADS, 2019.**

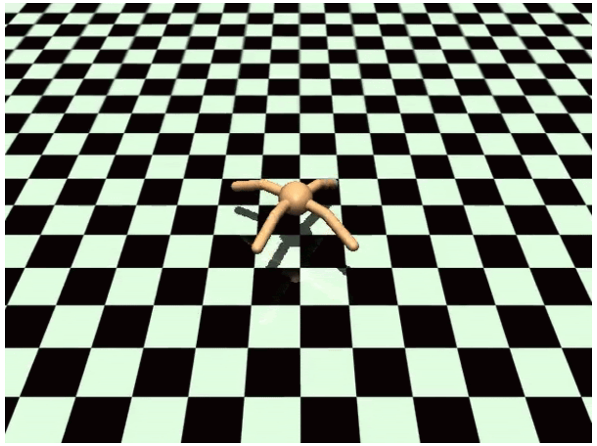
Skill-dynamics model

We are learning a skill-dynamics model $q(s' \mid s, z)$

compared to conventional global dynamics $p(s' \mid s, a)$

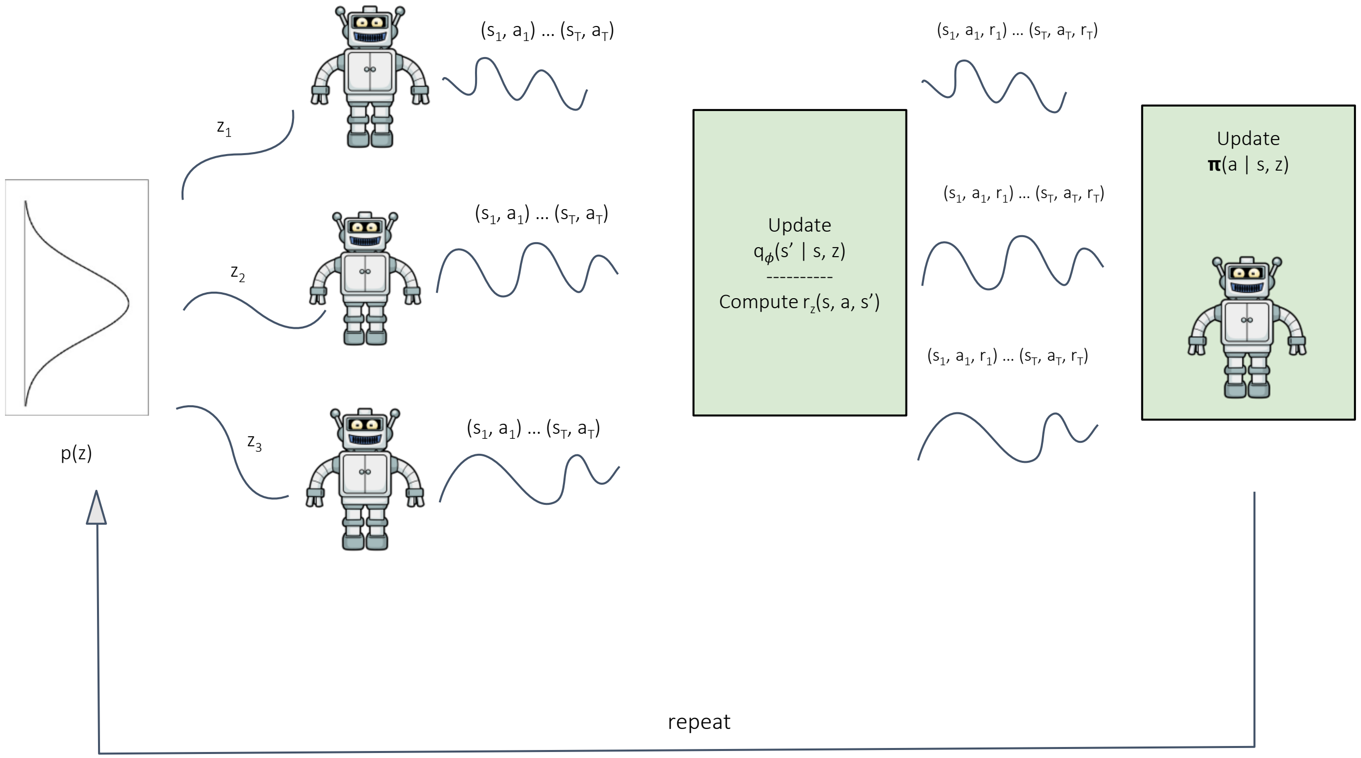
Skills are optimized specifically to make skill-dynamics easier to model





Sharma, Gu, Levine, Kumar, Hausman, **DADS, 2019.**

DADS algorithm

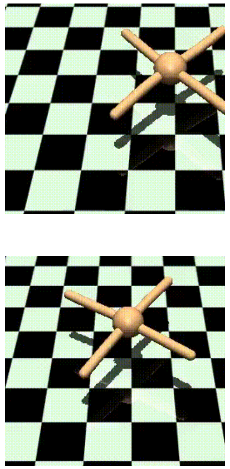


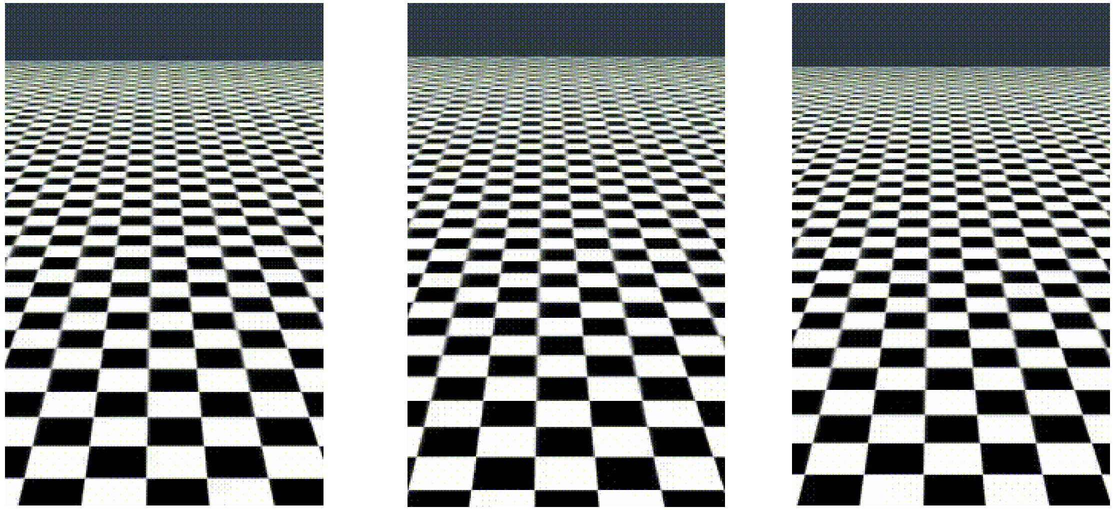
Algorithm 1: Dynamics-Aware Discovery of Skills (DADS)

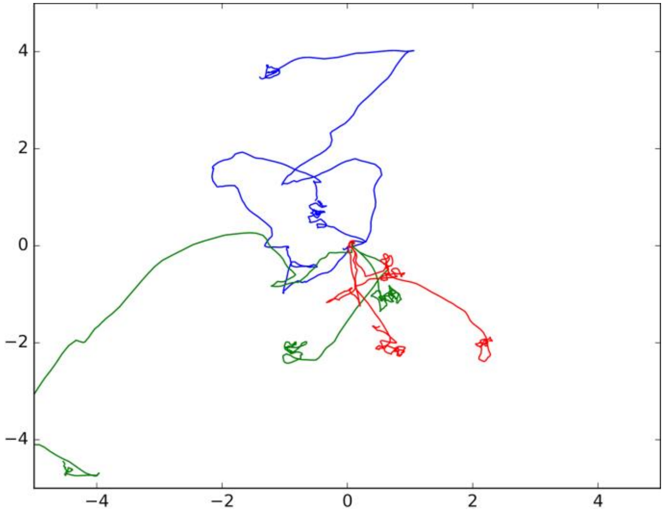
Initialize π, q_ϕ;
while *not converged* **do**
  Sample a skill $z \sim p(z)$ every episode;
  Collect new M on-policy samples;
  Update q_ϕ using K_1 steps of gradient descent on M transitions;
  Compute $r_z(s, a, s')$ for M transitions;
  Update π using any RL algorithm;
end

Sharma, Gu, Levine, Kumar, Hausman, DADS, 2019.

DADS results







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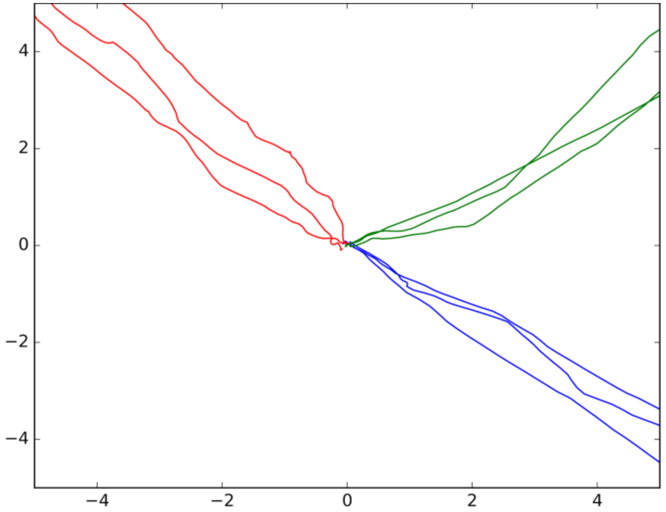
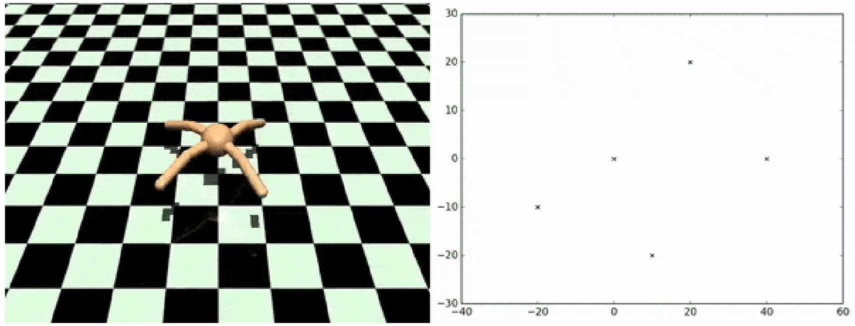
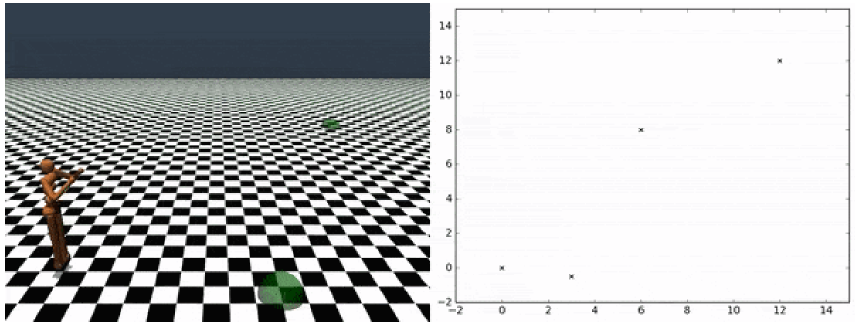


DADS

Using learned skills

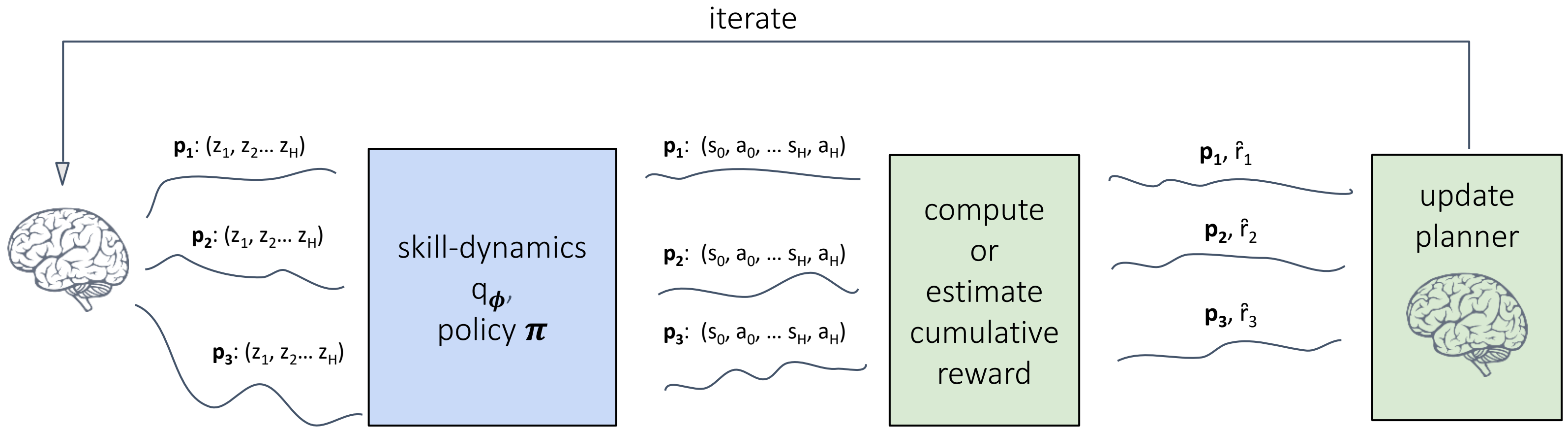




Use skill-dynamics for model-based planning

Plan for skills not actions

Tasks can be learned zero-shot



Summary

- Two skill discovery algorithms that use mutual information
- Predictability can be used as a proxy for “usefulness”
- Method that optimizes for both, predictability and diversity
- Model-based planning in the skill space
- Opens new avenues such as unsupervised meta-RL
    - Gupta et al. *Unsupervised Meta-Learning for RL*, 2018

The Plan

Information-theoretic concepts

Skill discovery

Using discovered skills

Hierarchical RL

Why Hierarchical RL?

Performing tasks at various levels of abstractions

Bake a cheesecake

Buy ingredients

Go to the store

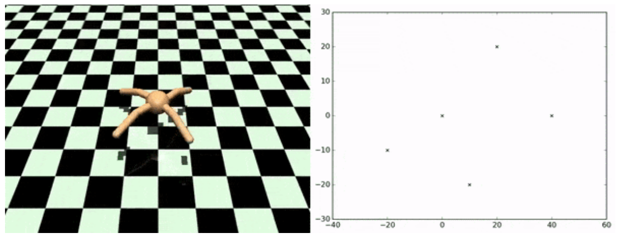
Walk to the door

Take a step

Contract muscle X

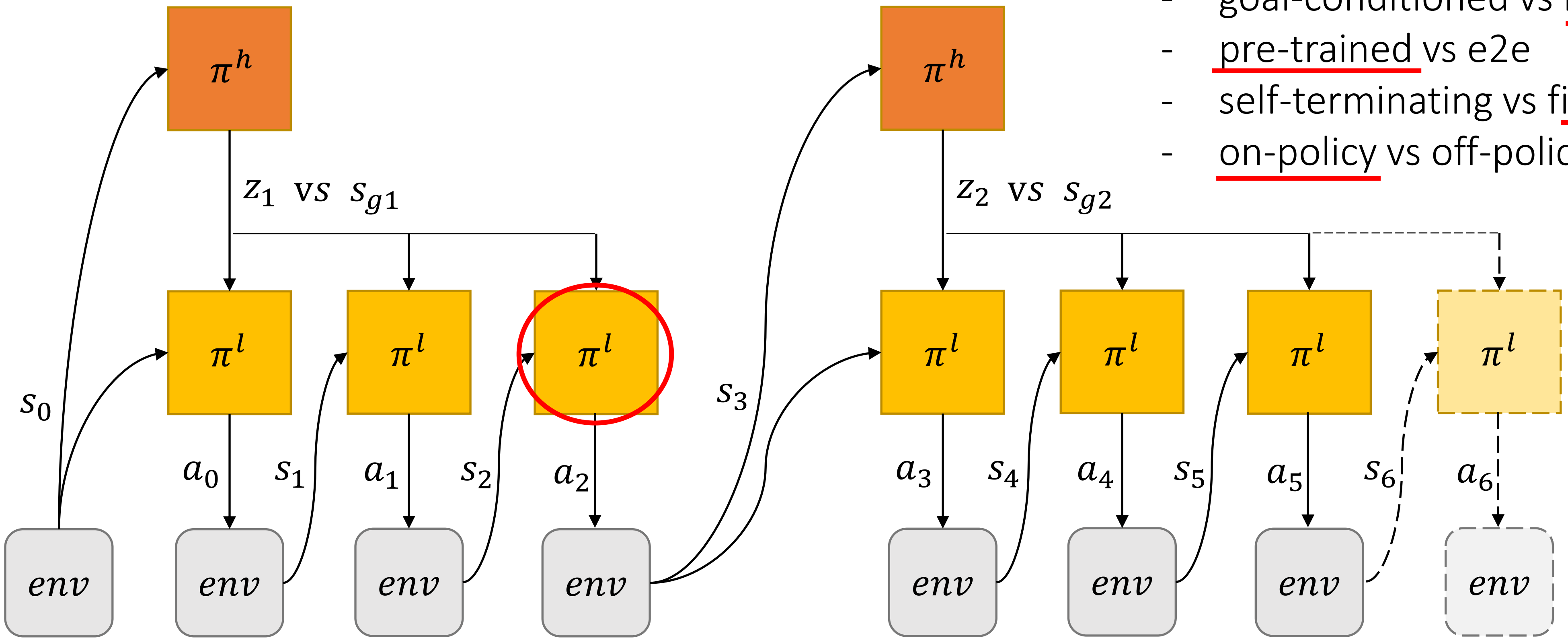
Exploration

Hierarchical RL – design choices



Design choices:

- goal-conditioned vs not
- pre-trained vs e2e
- self-terminating vs fixed rate
- on-policy vs off-policy



Learning Locomotor Controllers

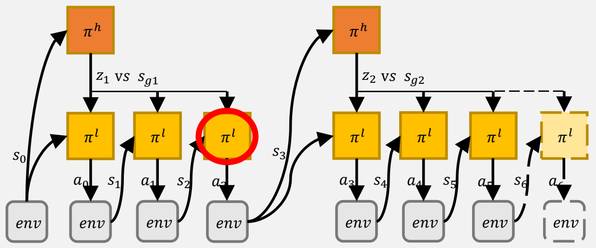
Command updated
every K steps

High-level
[redacted]

[redacted] w-level
ntroller

inform

- HL and LL trained separately
- Trained with policy gradients
- Hierarchical noise



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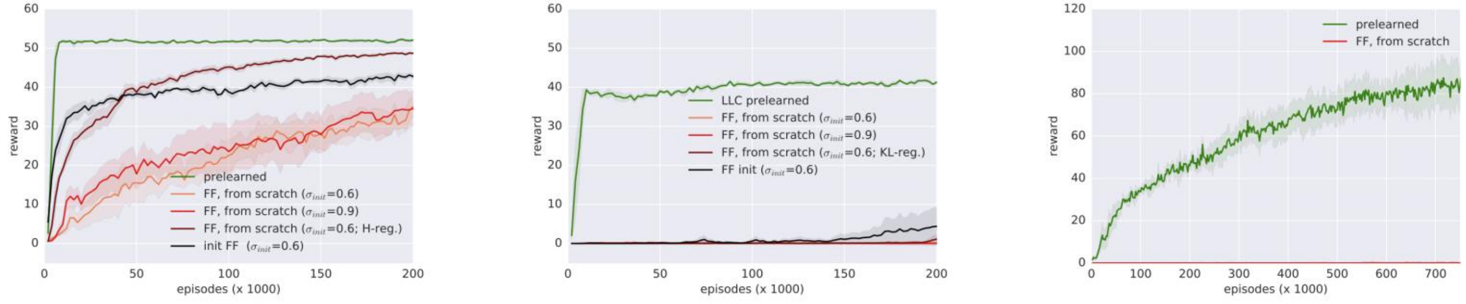
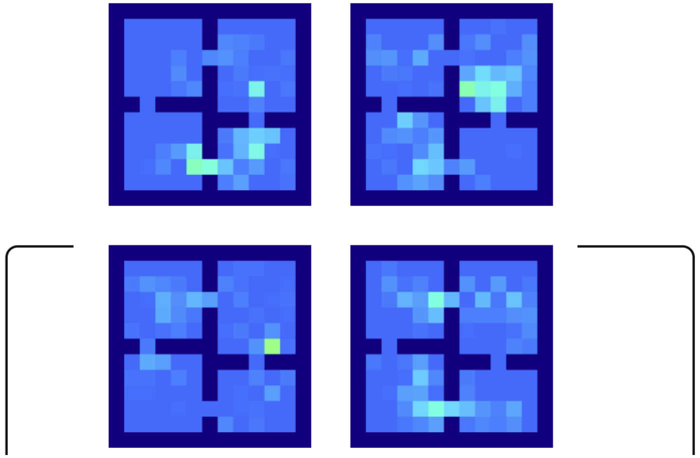


(a) target-seek (easy) (b) target-seek (hard) (c) soccer

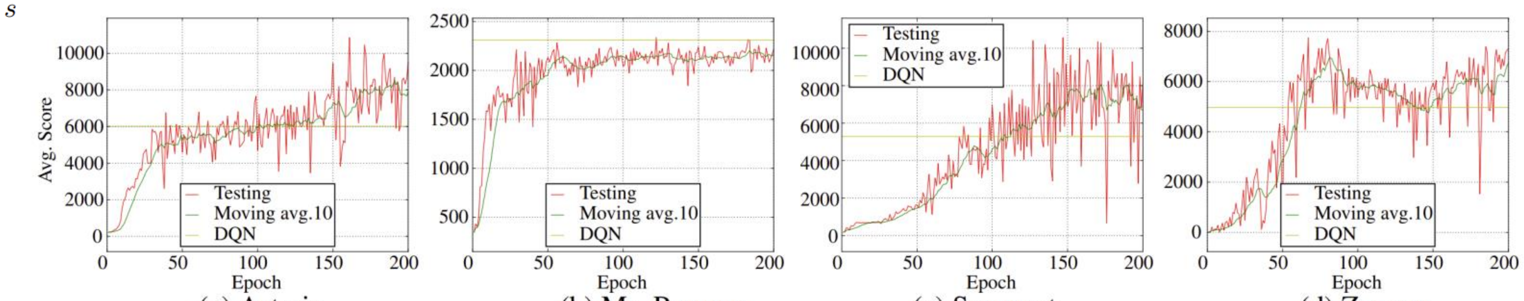
Heess, Wayne, Tassa, Lillicrap, Riedmiller, Silver, **Learning Locomotor Controllers, 2016.**

Option Critic

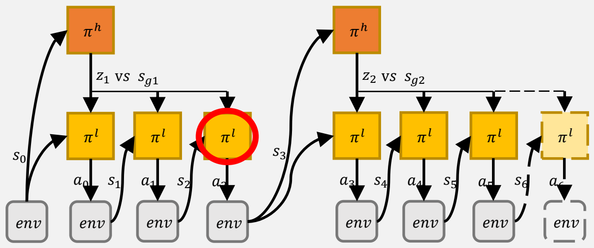
A Markovian option $\omega \in \Omega$ is a triple $(\mathcal{I}_\omega, \pi_\omega, \beta_\omega)$ in which $\mathcal{I}_\omega \subseteq \mathcal{S}$ is an initiation set, π_ω is an *intra-option* policy, and $\beta_\omega : \mathcal{S} \to [0,1]$ is a termination function. We also assume that $\forall s \in \mathcal{S}, \forall \omega \in \Omega : s \in \mathcal{I}_\omega$ (i.e., all options are available everywhere)



- Option is a self-terminating mini-policy
- Everything trained together with policy gradient



(a) Asterix (b) Ms. Pacman (c) Seaquest (d) Zaxxon



Design choices:

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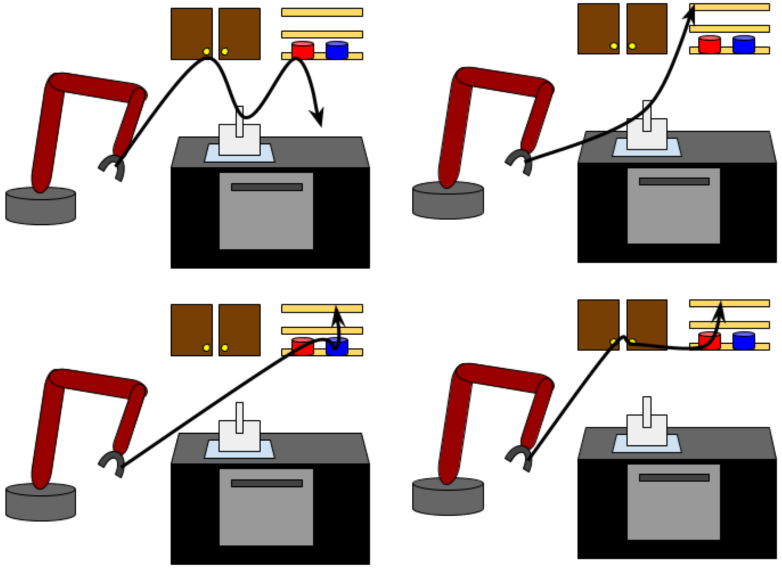
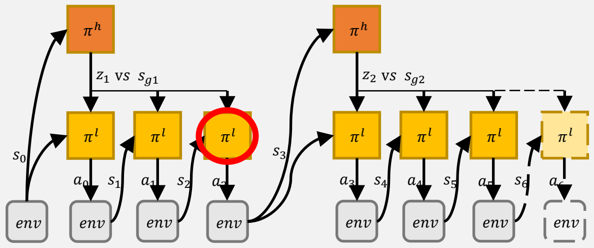
Bacon, Harb, Precup, **The Option-Critic Architecture, 2016.**

Relay Policy Learning





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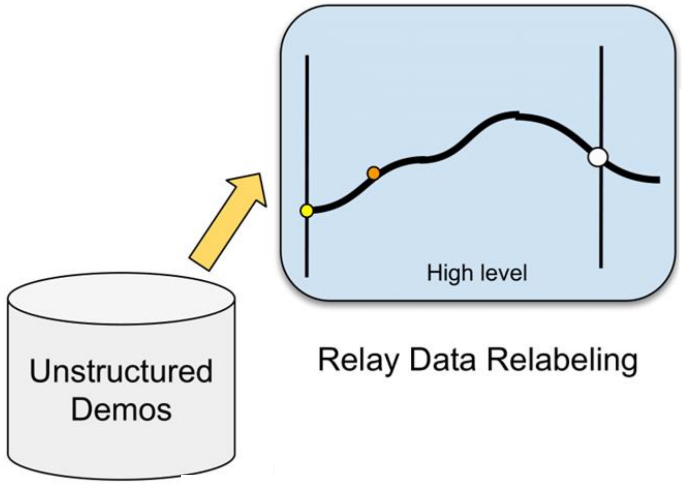
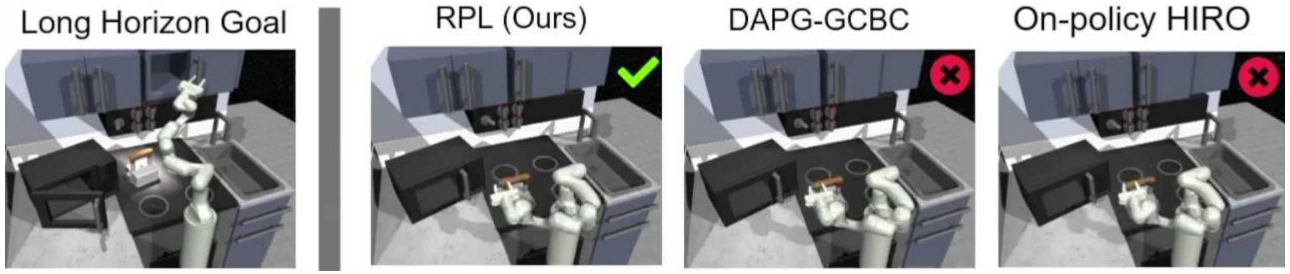
Gupta, Kumar, Lynch, Levine, Hausman, **Relay Policy Learning, 2019.**

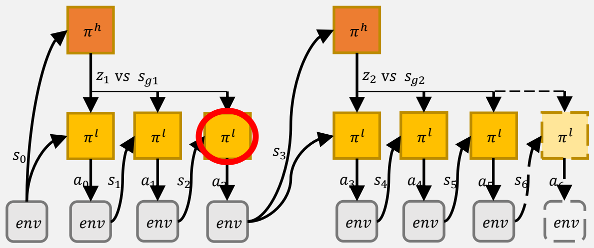
Relay Policy Learning



- Goal-conditioned policies with relabeling
- Demonstrations to pre-train everything
- On-policy



Gupta, Kumar, Lynch, Levine, Hausman, **Relay Policy Learning, 2019.**



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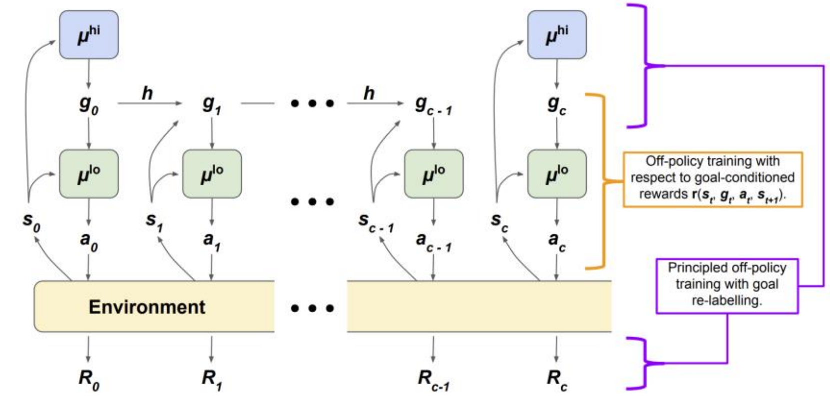
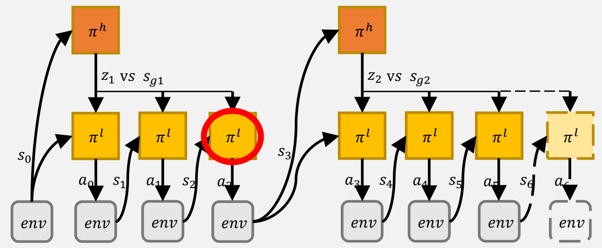
HIRO



1. Collect experience $s_t, g_t, a_t, R_t, \ldots$.
2. Train μ^{lo} with experience transitions $(s_t, g_t, a_t, r_t, s_{t+1}, g_{t+1})$ using g_t as additional state observation and reward given by goal-conditioned function $r_t = r(s_t, g_t, a_t, s_{t+1}) = -||s_t + g_t - s_{t+1}||_2$.
3. Train μ^{hi} on temporally-extended experience $(s_t, \tilde{g}_t, \sum R_{t:t+c-1}, s_{t+c})$, where $\tilde{g}_t$ is re-labelled high-level action to maximize probability of past low-level actions $a_{t:t+c-1}$.
4. Repeat.

Figure 2: The design and basic training of HIRO. The lower-level policy interacts directly with the environment. The higher-level policy instructs the lower-level policy via high-level actions, or goals, $g_t \in \mathbb{R}^{d_s}$ which it samples anew every c steps. On intermediate steps, a fixed goal transition function h determines the next step's goal. The goal simply instructs the lower-level policy to reach specific states, which allows the lower-level policy to easily learn from prior off-policy experience.



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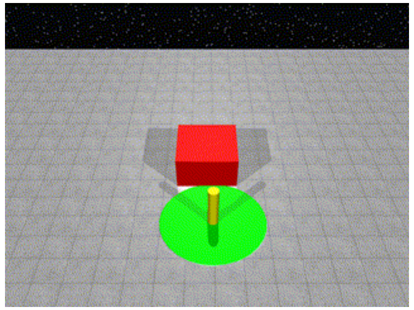
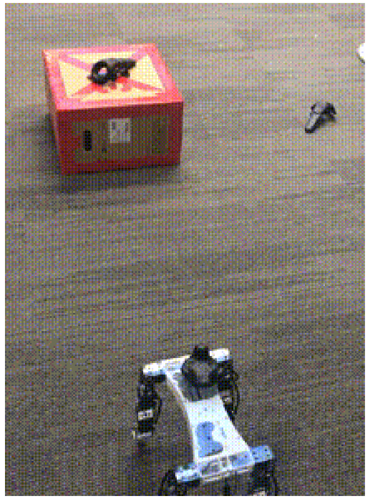
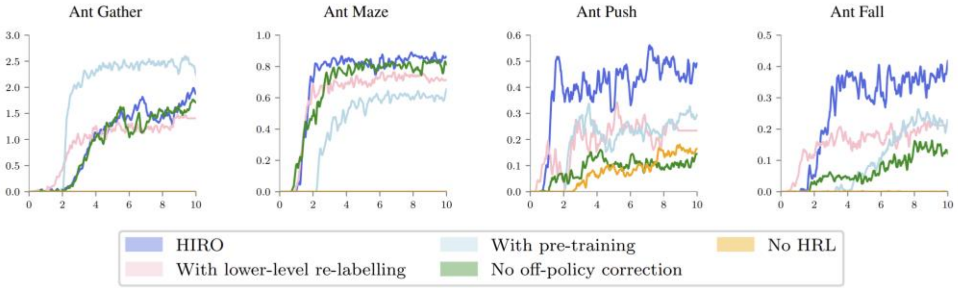




- Goal-conditioned policies with relabeling
- Off-policy training through off-policy corrections



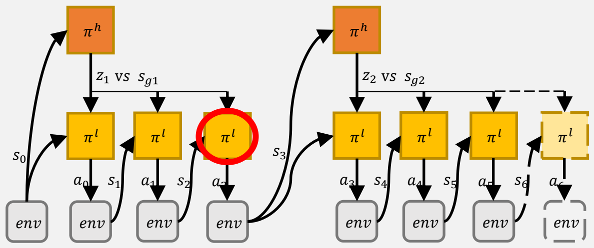
Nachum, Gu, Lee, Levine **HIRO, 2018.**

HRL Summary

- Multiple design choices and frameworks
- Helps with exploration and temporally extended tasks
- Can be difficult to get it to work
- Seems like a natural direction for harder RL problems

Hypothesis	Experiments	Important?
(H1) Temporal training	Figures 2, 3	Yes, but only for the use of multi-step rewards (n-step returns).
(H2) Temporal exploration	Figures 2, 4	Yes, and this is important even for non-hierarchical exploration.
(H3) Semantic training	Figure 3	No.
(H4) Semantic exploration	Figure 4	Yes, and this is important even for non-hierarchical exploration.

Figure 5: A summary of our conclusions on the benefits of hierarchy.



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Nachum, Lang, Lu, Gu, Lee, Levine, Why Does Hierarchy (Sometimes) Work? 2019.

Recap

Key learning goals:

- Understand the concept of a skill and basic algorithms in this space
- Overview of hierarchical RL algorithms

Skill discovery/learning:

- Connected to information-theoretic measures like mutual information
- Unsupervised but difficult to use in complex environments

Hierarchical RL:

- Many different options/methods
- Designed to cope with longer-horizon tasks
- Largely unsolved

Next

Monday – no lecture

Guest lecture – Anna Goldie on various RL applications including LLMs and chip design