Exploration (Part 2)

CS 285

Instructor: Sergey Levine
UC Berkeley

Recap: what's the problem?

this is easy (mostly)

Why?

this is impossible

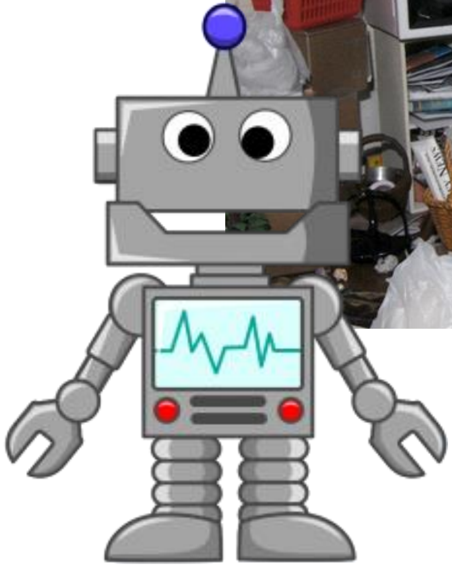
Unsupervised learning of diverse behaviors

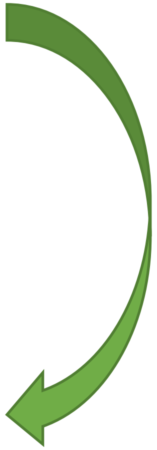
What if we want to recover diverse behavior **without any reward function at all**?

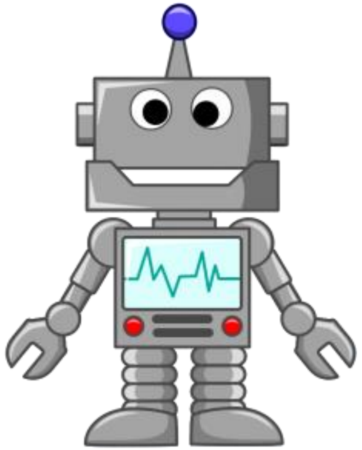
Why?

- *Learn skills without supervision, then use them to accomplish goals*
- *Learn sub-skills to use with hierarchical reinforcement learning*
- *Explore the space of possible behaviors*

An Example Scenario







How can you prepare for an **unknown** future goal?

training time: unsupervised

In this lecture…

- Definitions & concepts from information theory
- Learning without a reward function by reaching goals
- A *state distribution-matching* formulation of reinforcement learning
- Is coverage of valid states a *good* exploration objective?
- Beyond state covering: covering the *space of skills*

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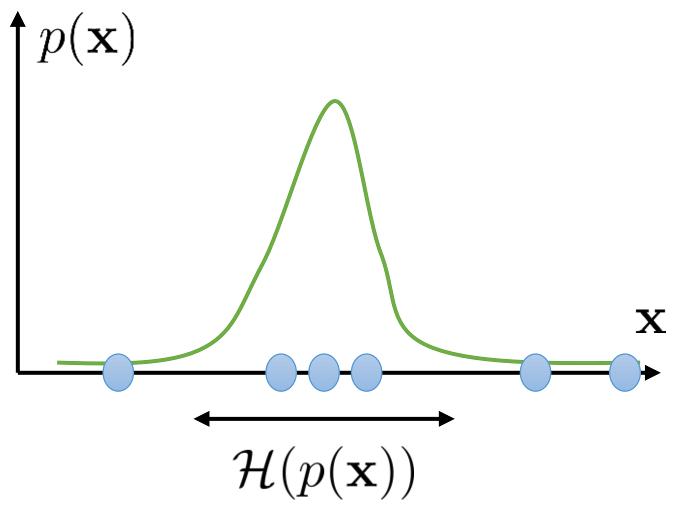
Some useful identities

$p(\mathbf{x})$ 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



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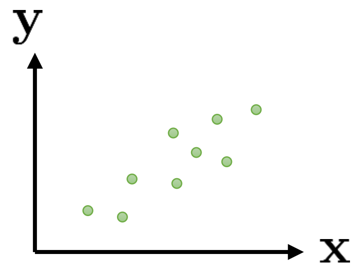
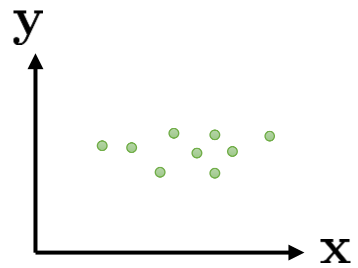


high MI: $\mathbf{x}$ and $\mathbf{y}$ are *dependent*

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

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

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



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

Information theoretic quantities in RL

$\pi(\mathbf{s})$ state *marginal* distribution of policy π

quantifies *coverage*

$\mathcal{H}(\pi(\mathbf{s}))$ state *marginal* entropy of policy π

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

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

can be viewed as quantifying "control authority" in an information-theoretic way

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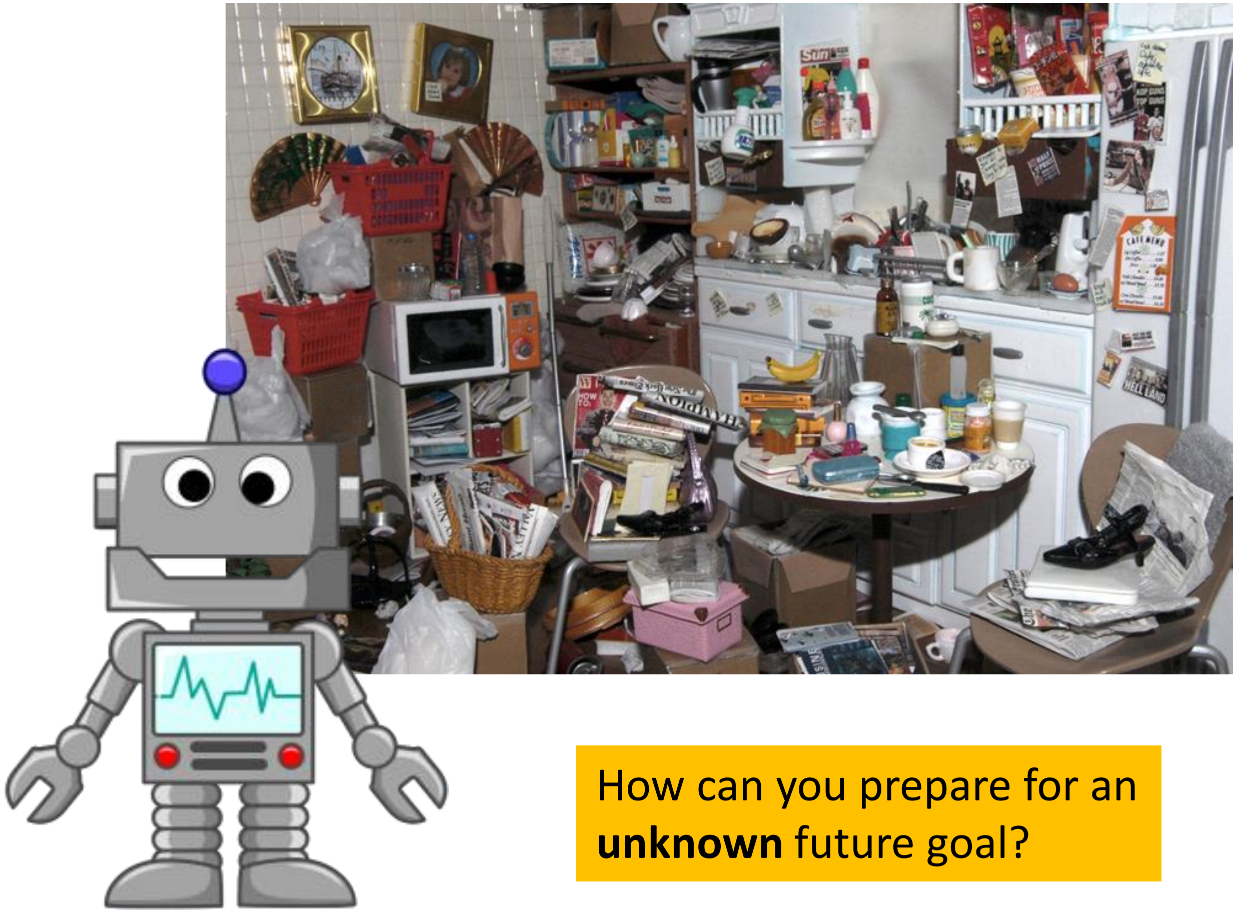

How can you prepare for an **unknown** future goal?

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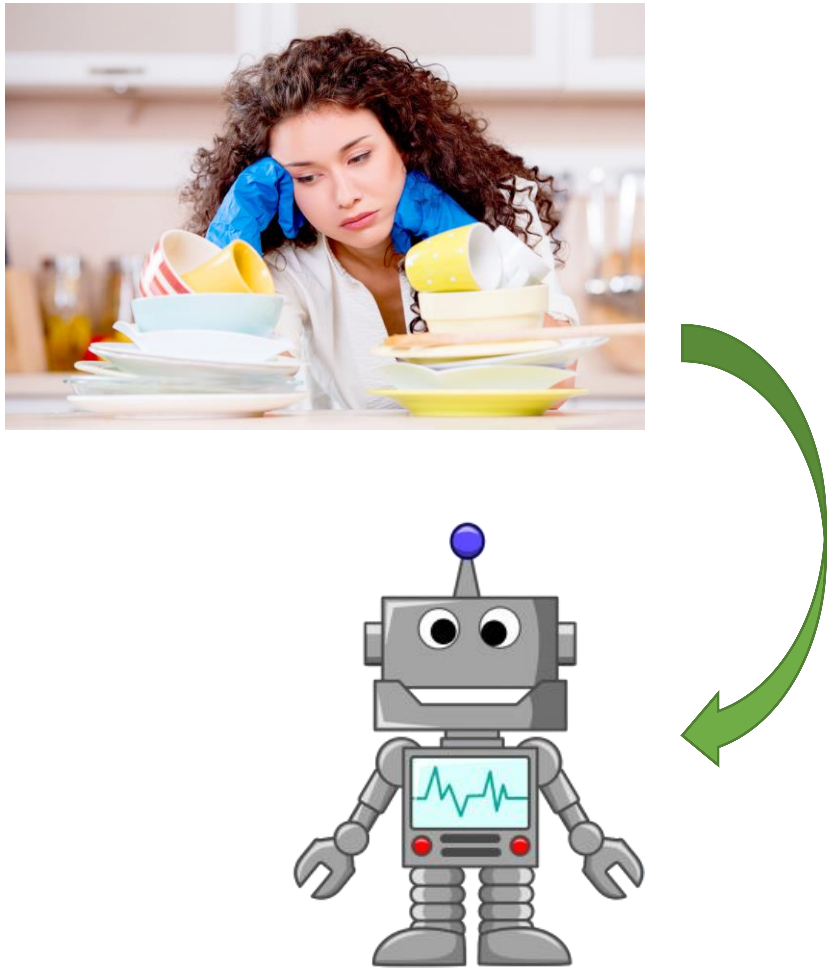
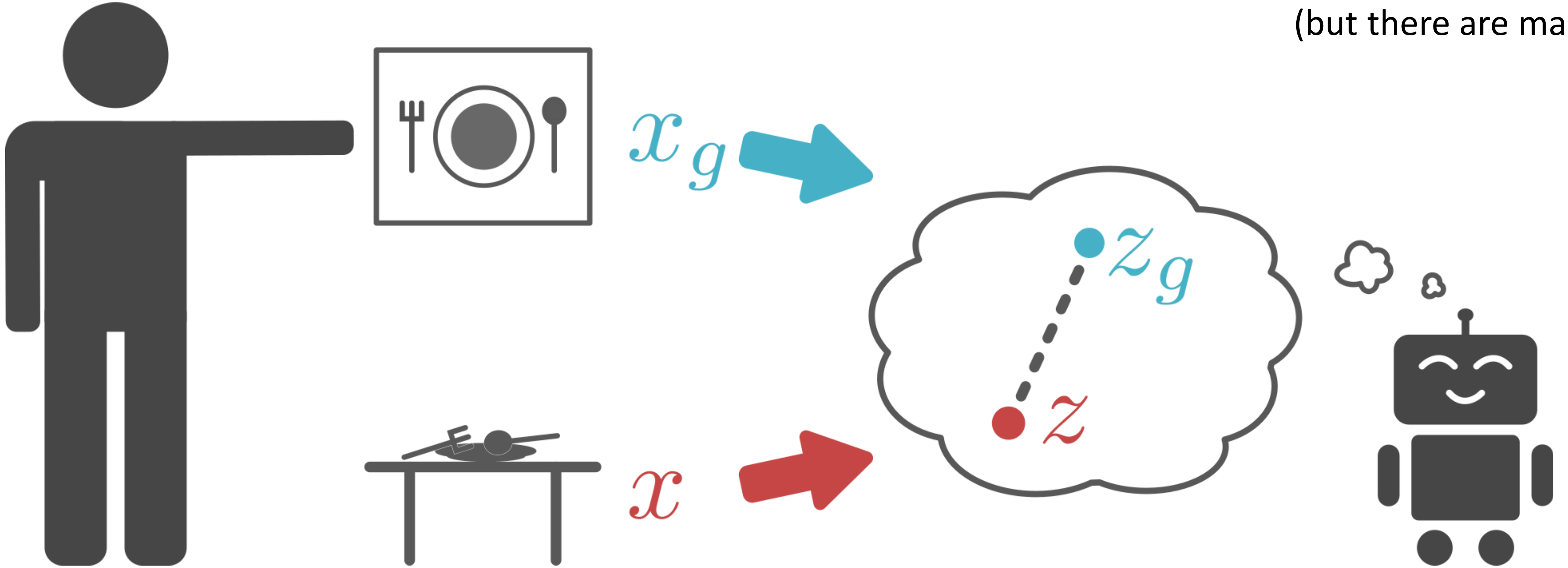
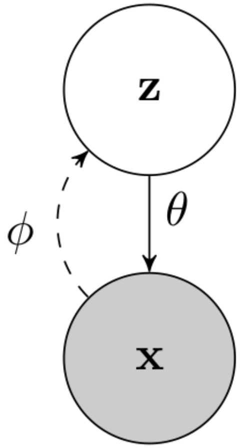


Learn without any rewards at all

VAE (Kingma & Welling '13)

(but there are many other choices)





Nair*, Pong*, Bahl, Dalal, Lin, L. **Visual Reinforcement Learning with Imagined Goals**. '18
Dalal*, Pong*, Lin*, Nair, Bahl, Levine. **Skew-Fit: State-Covering Self-Supervised Reinforcement Learning.** '19

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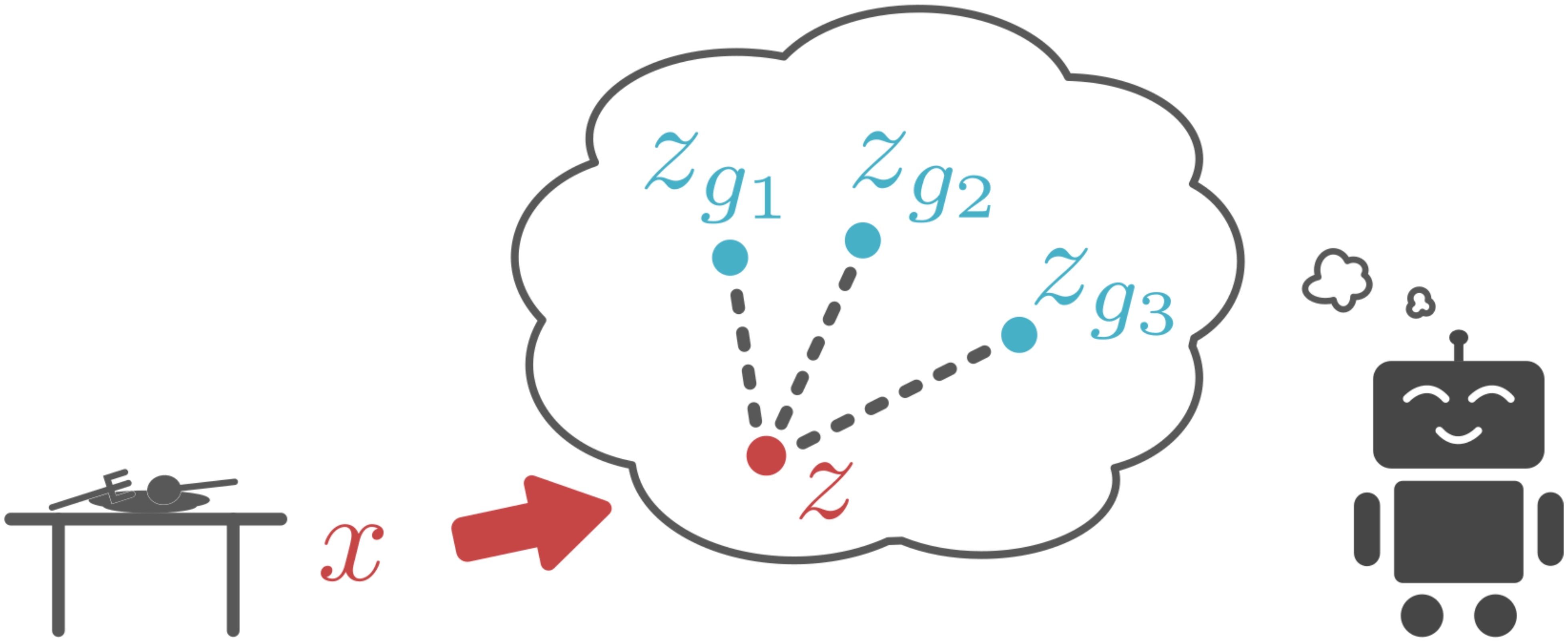

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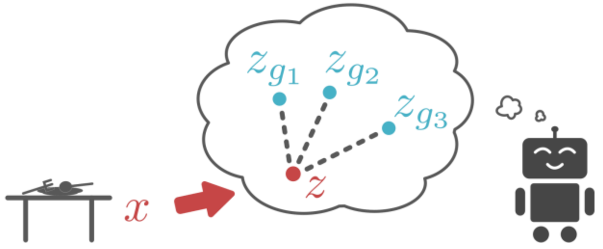
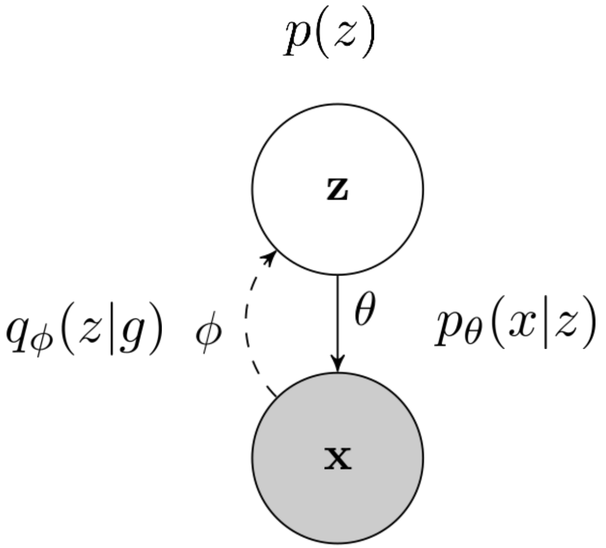
Learn without any rewards at all

1. Propose goal: $z_g \sim p(z)$, $x_g \sim p_\theta(x_g|z_g)$
2. Attempt to reach goal using $\pi(a|x, x_g)$, reach $\bar{x}$
3. Use data to update π
4. Use data to update $p_\theta(x_g|z_g)$, $q_\phi(z_g|x_g)$





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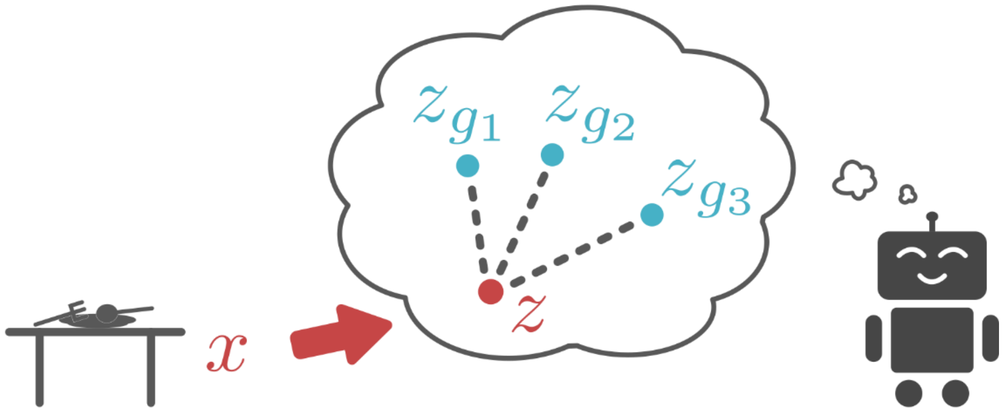
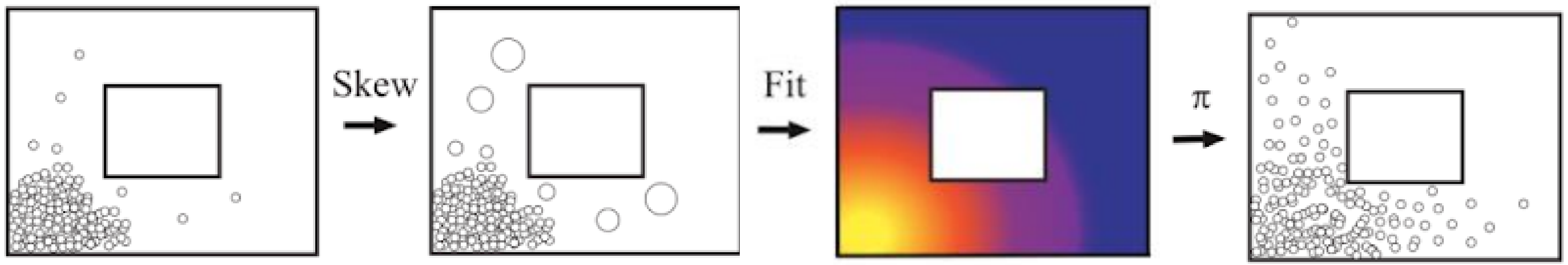
How do we get diverse goals?





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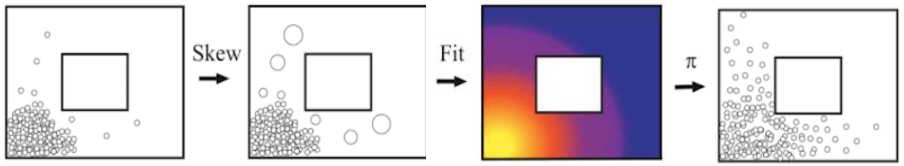
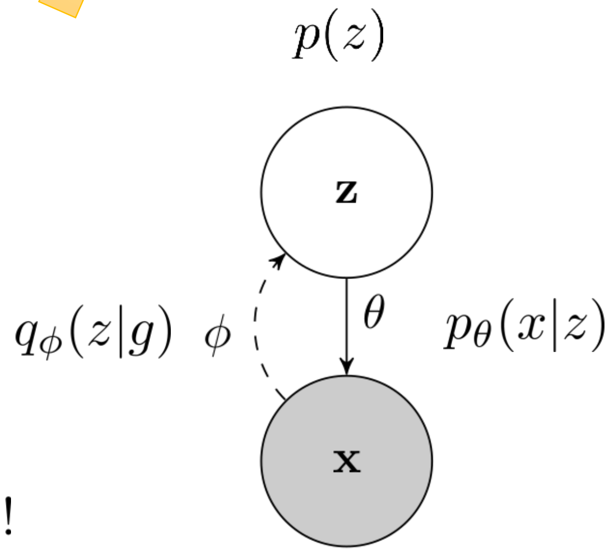


standard MLE: $\theta, \phi \leftarrow \arg\max_{\theta,\phi} E[\log p(\bar{x})]$

weighted MLE: $\theta, \phi \leftarrow \arg\max_{\theta,\phi} E[w(\bar{x}) \log p(\bar{x})]$

$w(\bar{x}) = p_\theta(\bar{x})^\alpha$

key result: for any $\alpha \in [-1, 0)$, entropy $\mathcal{H}(p_\theta(x))$ increases!



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How do we get diverse goals?

what is the objective?

$$\max \mathcal{H}(p(G)) - \mathcal{H}(p(G|S))$$

goals get higher entropy due to Skew-Fit

what does RL do?

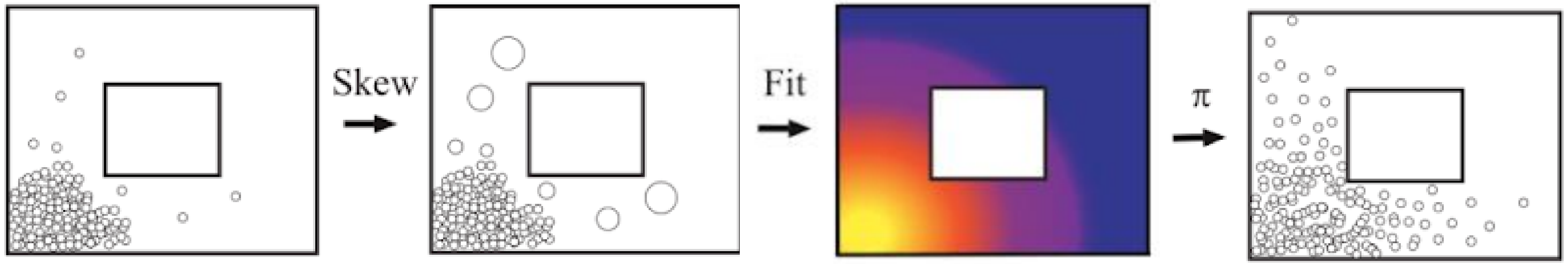
$\pi(a|S,G)$ trained to reach goal G

as π gets better, final state S gets close to G

that means $p(G|S)$ becomes more deterministic!

goal — final state

$$w(\bar{x}) = p_\theta(\bar{x})^\alpha$$
$$\alpha \in [-1, 0)$$



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How do we get diverse goals?

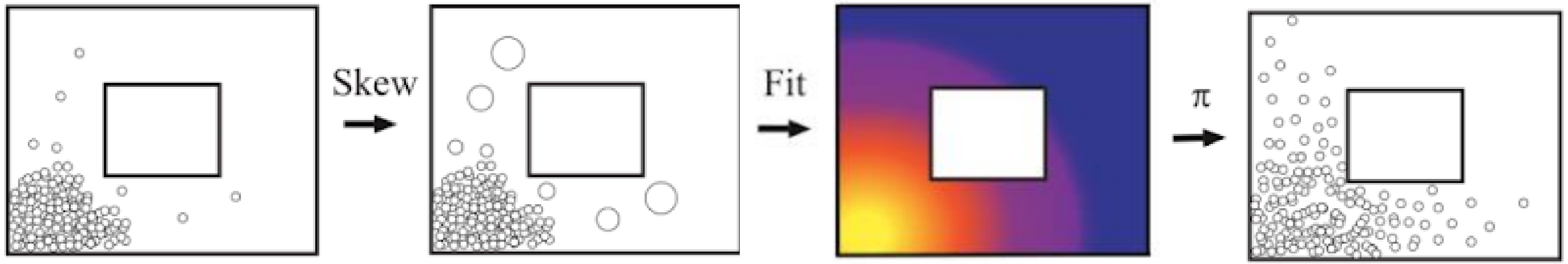
what is the objective?

$$\max \mathcal{H}(p(G)) - \mathcal{H}(p(G|S)) = \max \mathcal{I}(S;G)$$

maximizing mutual information between S and G leads to

good exploration (state coverage) – $\mathcal{H}(p(G))$

effective goal reaching – $\mathcal{H}(p(G|S))$



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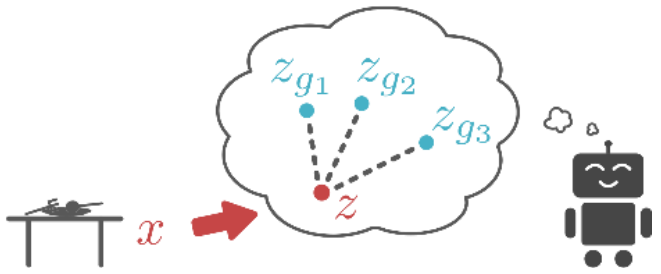
Reinforcement learning with *imagined* goals



imagined goal

RL episode

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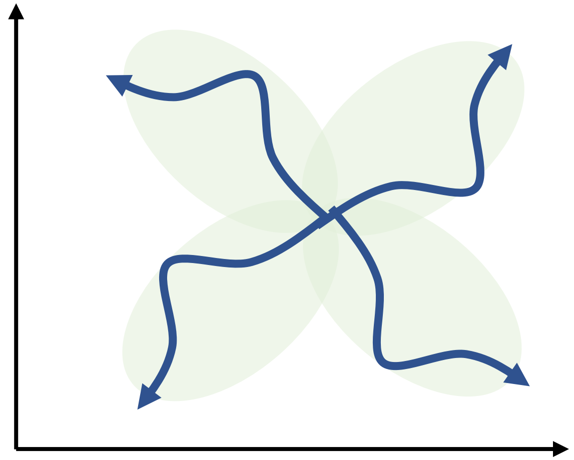
Aside: exploration with intrinsic motivation



common method for exploration:

incentivize policy $\pi(\mathbf{a}|\mathbf{s})$ to explore diverse states

...before seeing any reward

reward visiting **novel** states

if a state is visited *often*, it is not *novel*

$\Rightarrow$ add an exploration bonus to reward: $\tilde{r}(\mathbf{s}) = r(\mathbf{s}) - \log p_\pi(\mathbf{s})$

state density under $\pi(\mathbf{a}|\mathbf{s})$

1. update $\pi(\mathbf{a}|\mathbf{s})$ to maximize $E_\pi[\tilde{r}(\mathbf{s})]$
2. update $p_\pi(\mathbf{s})$ to fit state marginal

Can we use this for state marginal matching?

the state marginal matching problem: learn $\pi(\mathbf{a}|\mathbf{s})$ so as to minimze $D_{\mathrm{KL}}(p_\pi(\mathbf{s})\|p^\star(\mathbf{s}))$

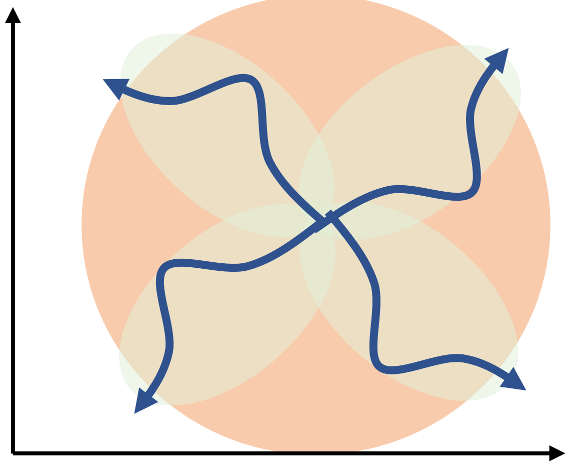
target state density

idea: can we use intrinsic motivation?

$$\tilde{r}(\mathbf{s}) = \log p^\star(\mathbf{s}) - \log p_\pi(\mathbf{s})$$

this does **not** perform marginal matching!

1. learn $\pi^k(\mathbf{a}|\mathbf{s})$ to maximize $E_\pi[\tilde{r}^k(\mathbf{s})]$
2. ~~update $p_{\pi^k}(\mathbf{s})$ to fit state marginal~~
2. update $p_{\pi^k}(\mathbf{s})$ to fit *all states seen so far*
3. return $\pi^\star(\mathbf{a}|\mathbf{s}) = \sum_k \pi^k(\mathbf{a}|\mathbf{s})$



special case: $\log p^\star(\mathbf{s}) = C \Rightarrow$ *uniform* target

$$D_{\mathrm{KL}}(p_\pi(\mathbf{s})\|U(\mathbf{s})) = \mathcal{H}(p_\pi(\mathbf{s}))$$

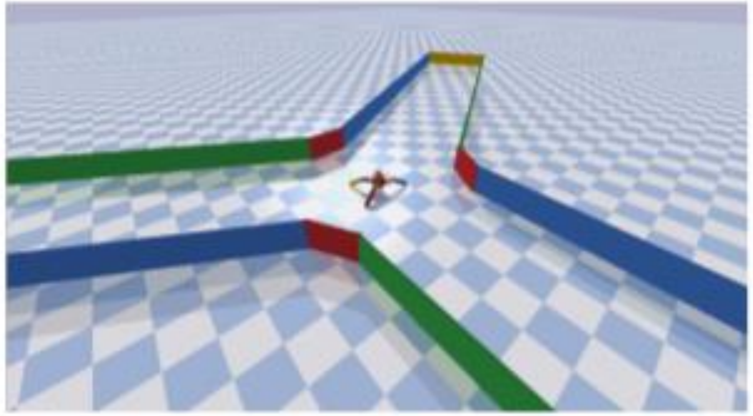
this **does** perform marginal matching!

$p_\pi(\mathbf{s}) = p^\star(\mathbf{s})$ is Nash equilibrium of two player game between π^k and p_{π^k}

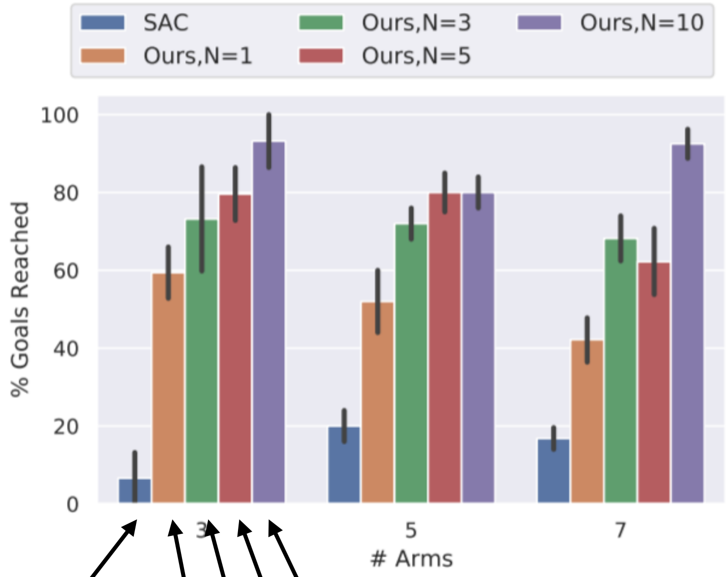
Lee*, Eysenbach*, Parisotto*, Xing, Levine, Salakhutdinov. **Efficient Exploration via State Marginal Matching**
See also: Hazan, Kakade, Singh, Van Soest. **Provably Efficient Maximum Entropy Exploration**

State marginal matching for exploration

the state marginal matching problem: learn $\pi(\mathbf{a}|\mathbf{s})$ so as to minimze $D_{\mathrm{KL}}(p_\pi(\mathbf{s}) \| p^\star(\mathbf{s}))$



much better coverage!



MaxEnt on actions

variants of SMM

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Is state entropy *really* a good objective?

Skew-Fit: $\max \mathcal{H}(p(G)) - \mathcal{H}(p(G|S)) = \max \mathcal{I}(S;G)$ ← more or less the same thing

SMM (special case where $p^\star(\mathbf{s}) = C$): $\max \mathcal{H}(p_\pi(S))$ ← more or less the same thing

When is this a good idea?

"Eysenbach's Theorem" (not really what it's called)

(follows trivially from classic maximum entropy modeling)

at test time, an *adversary* will choose the *worst* goal G

which goal distribution should you use for *training*?

answer: choose $p(G) = \arg\max_p \mathcal{H}(p(G))$

See also: Hazan, Kakade, Singh, Van Soest. **Provably Efficient Maximum Entropy Exploration**

Gupta, Eysenbach, Finn, Levine. **Unsupervised Meta-Learning for Reinforcement Learning**

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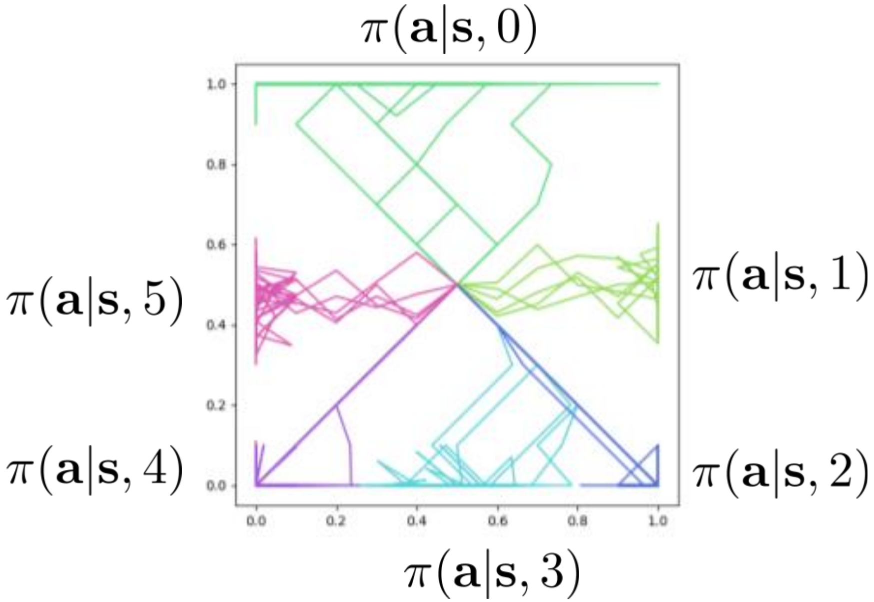
Learning diverse skills

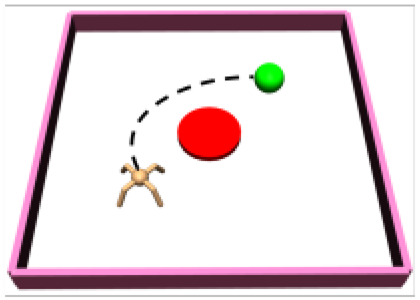
$$\pi(\mathbf{a}|\mathbf{s}, z)$$

↑ task index



Reaching diverse **goals** is not the same as performing diverse **tasks**

not all behaviors can be captured by **goal-reaching**



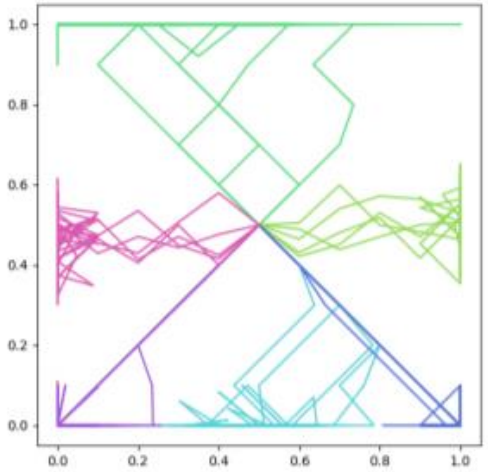
Intuition: different **skills** should visit different **state-space regions**

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

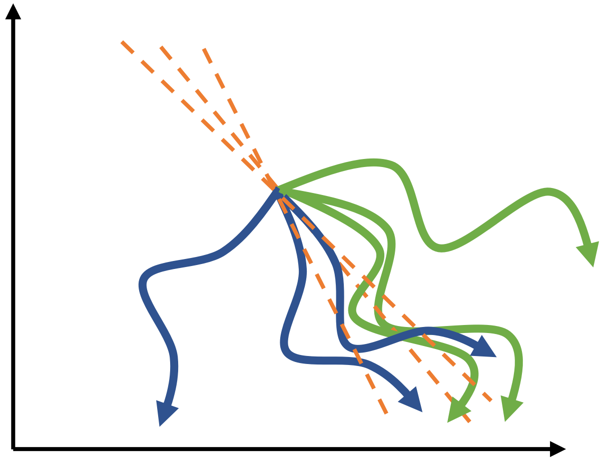
Diversity-promoting reward function

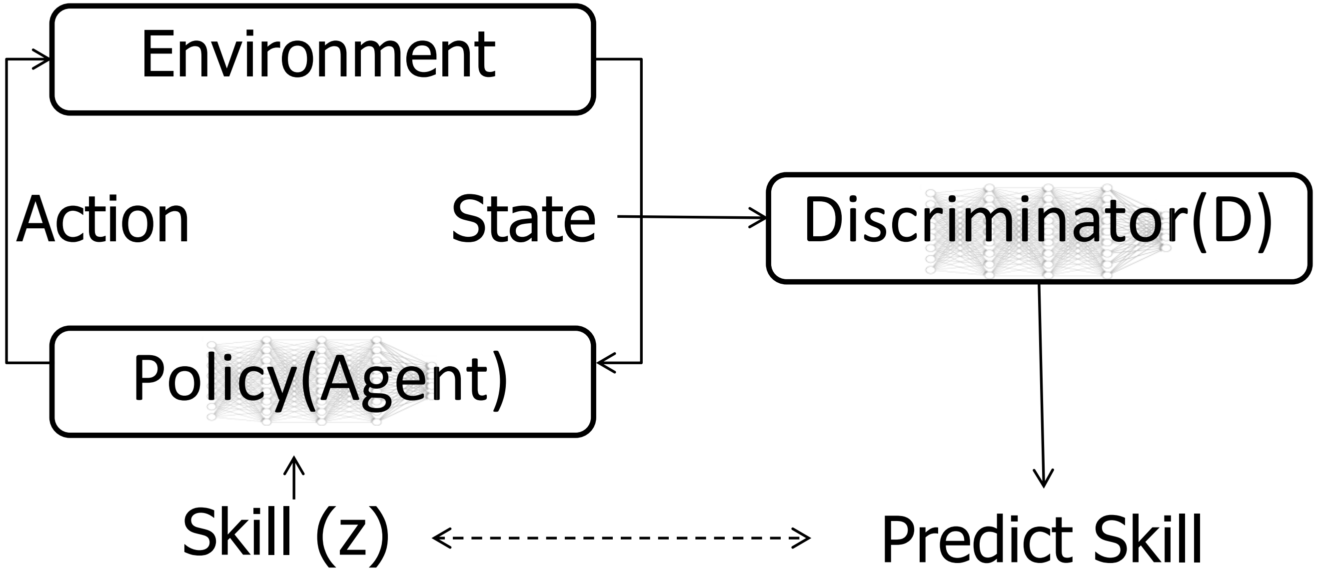
$$\pi(\mathbf{a}|\mathbf{s}, z) = \arg\max_{\pi} \sum_{z} E_{\mathbf{s}\sim\pi(\mathbf{s}|z)}[r(\mathbf{s}, z)]$$

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



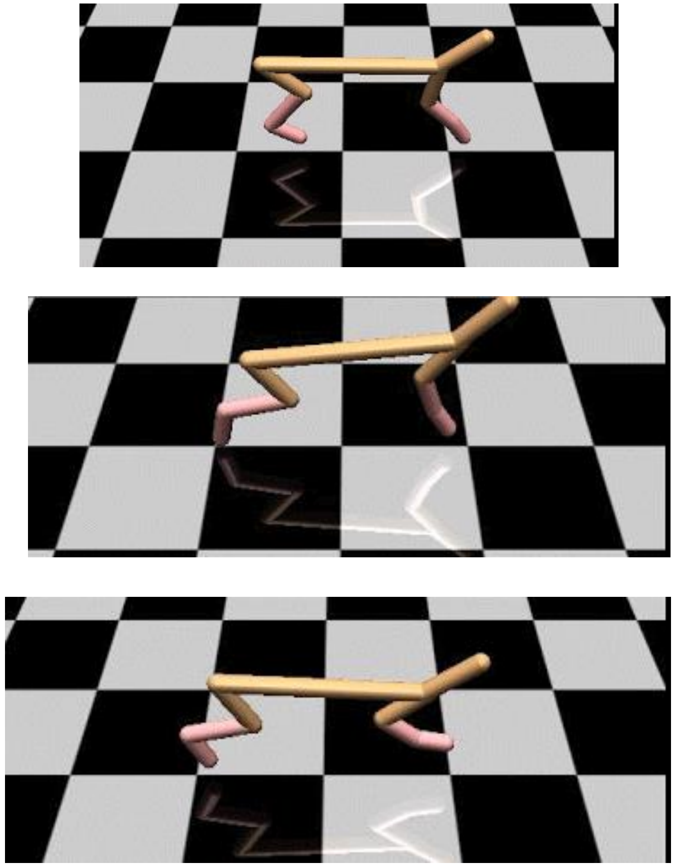
$$r(\mathbf{s}, z) = \log p(z|\mathbf{s})$$



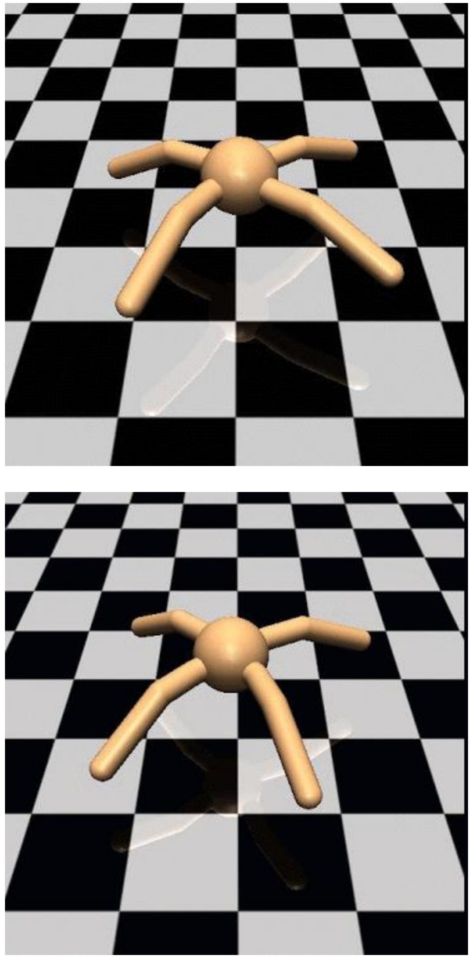


Eysenbach, Gupta, Ibarz, Levine. **Diversity is All You Need.**

Examples of learned tasks



Cheetah



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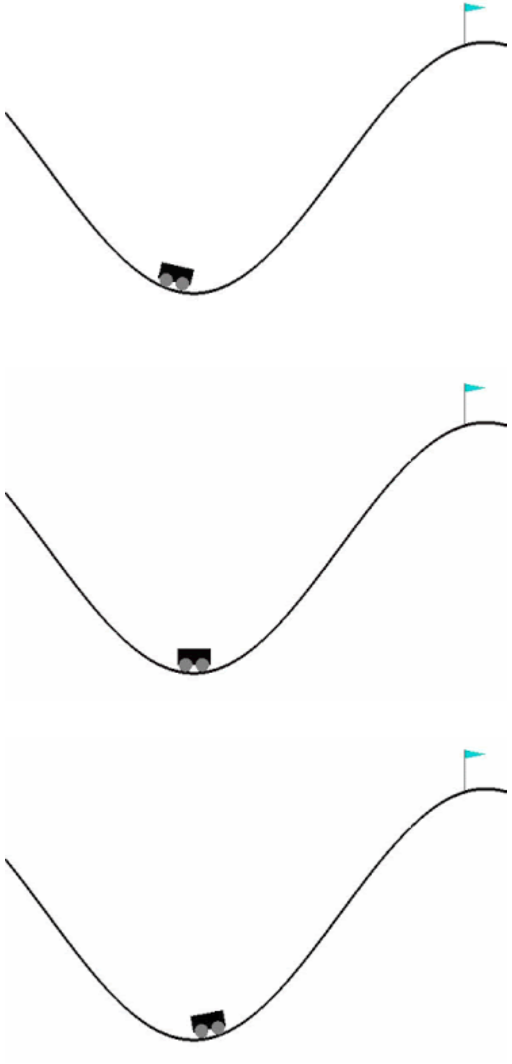

Mountain car

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