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Reinforcement Learning



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Playing Atari with Deep Reinforcement Learning



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$\mathcal{E} \rightarrow$ environment

actions, observations, rewards

$a_t \rightarrow$ action

$\mathcal{A} = \{1, \dots, K\} \rightarrow$ set of legal actions

$x_t \in \mathbb{R}^d \rightarrow$ image

$r_t \rightarrow$ reward

partially observed task

$s_t = x_1, a_1, x_2, a_2, \dots, a_{t-1}, x_t \rightarrow$ state

MDP: Markov Decision Process

$$R_t = \sum_{t'=t}^T \gamma^{t'-t} r_{t'} \rightarrow \text{future discounted return at time } t$$

$Q^*(s, a) \rightarrow$ optimal action-value function

$\pi \rightarrow$ policy mapping sequences s to actions
(distribution over actions)

$$Q^*(s, a) = \max_{\pi} \mathbb{E}[R_t | s_t = s, a_t = a, \pi]$$

Bellman Equation

$$Q^*(s, a) = \mathbb{E}_{s' \sim \mathcal{E}} [r + \gamma \max_{a'} Q^*(s', a') | s, a]$$

Value Iteration Algorithm

$$Q_{i+1}(s, a) = \mathbb{E}[r + \gamma \max_{a'} Q_i(s', a') | s, a]$$

$Q(s, a; \theta) \approx Q^*(s, a) \rightarrow$ Q-Network

$$L_i(\theta_i) = \mathbb{E}_{s, a \sim \rho(\cdot)} [(y_i - Q(s, a; \theta_i))^2]$$

$$y_i = \mathbb{E}_{s' \sim \mathcal{E}} [r + \gamma \max_{a'} Q(s', a'; \theta_{i-1}) | s, a]$$

target for iteration i

$\rho(s, a) \rightarrow$ prob. distribution over sequences & actions
(behavior distribution)

model free: no explicit construction of an estimator for \mathcal{E}

off-policy: greedy strategy $a^* = \max_a Q(s, a; \theta)$

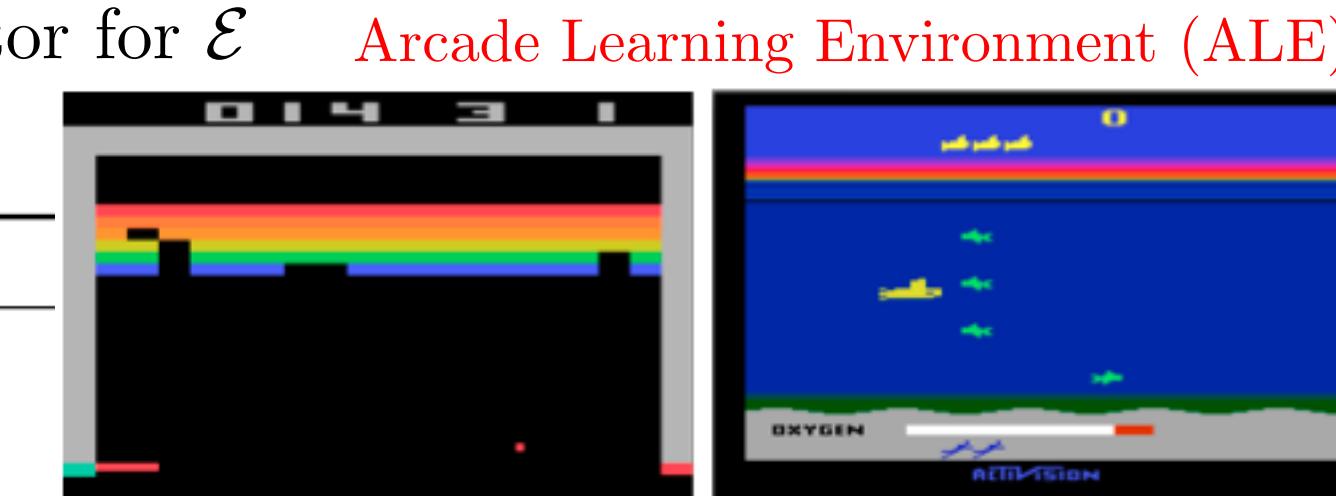
Experience Replay

$e_t = (s_t, a_t, r_t, s_{t+1}) \rightarrow$ agent's experience

$\mathcal{D} = e_1, e_2, \dots, e_N \rightarrow$ replay memory

Input to Q-Network: state representation

Output of DQN: predicted Q-values of individual actions



Algorithm 1 Deep Q-learning with Experience Replay

Initialize replay memory \mathcal{D} to capacity N

Initialize action-value function Q with random weights

for episode = 1, M **do**

 Initialise sequence $s_1 = \{x_1\}$ and preprocessed sequenced $\phi_1 = \phi(s_1)$

for $t = 1, T$ **do**

 With probability ϵ select a random action a_t ϵ -greedy $\rightarrow \begin{cases} \text{greedy action} & \text{with prob. } 1 - \epsilon \\ \text{random action} & \text{with prob. } \epsilon \end{cases}$
 otherwise select $a_t = \max_a Q^*(\phi(s_t), a; \theta)$

 Execute action a_t in emulator and observe reward r_t and image x_{t+1}

 Set $s_{t+1} = s_t, a_t, x_{t+1}$ and preprocess $\phi_{t+1} = \phi(s_{t+1}) \rightarrow$ last four frames of a history (stacked)

 Store transition $(\phi_t, a_t, r_t, \phi_{t+1})$ in \mathcal{D}

 Sample random minibatch of transitions $(\phi_j, a_j, r_j, \phi_{j+1})$ from \mathcal{D}

 Set $y_j = \begin{cases} r_j & \text{for terminal } \phi_{j+1} \\ r_j + \gamma \max_{a'} Q(\phi_{j+1}, a'; \theta) & \text{for non-terminal } \phi_{j+1} \end{cases}$

 Perform a gradient descent step on $(y_j - Q(\phi_j, a_j; \theta))^2$

end for

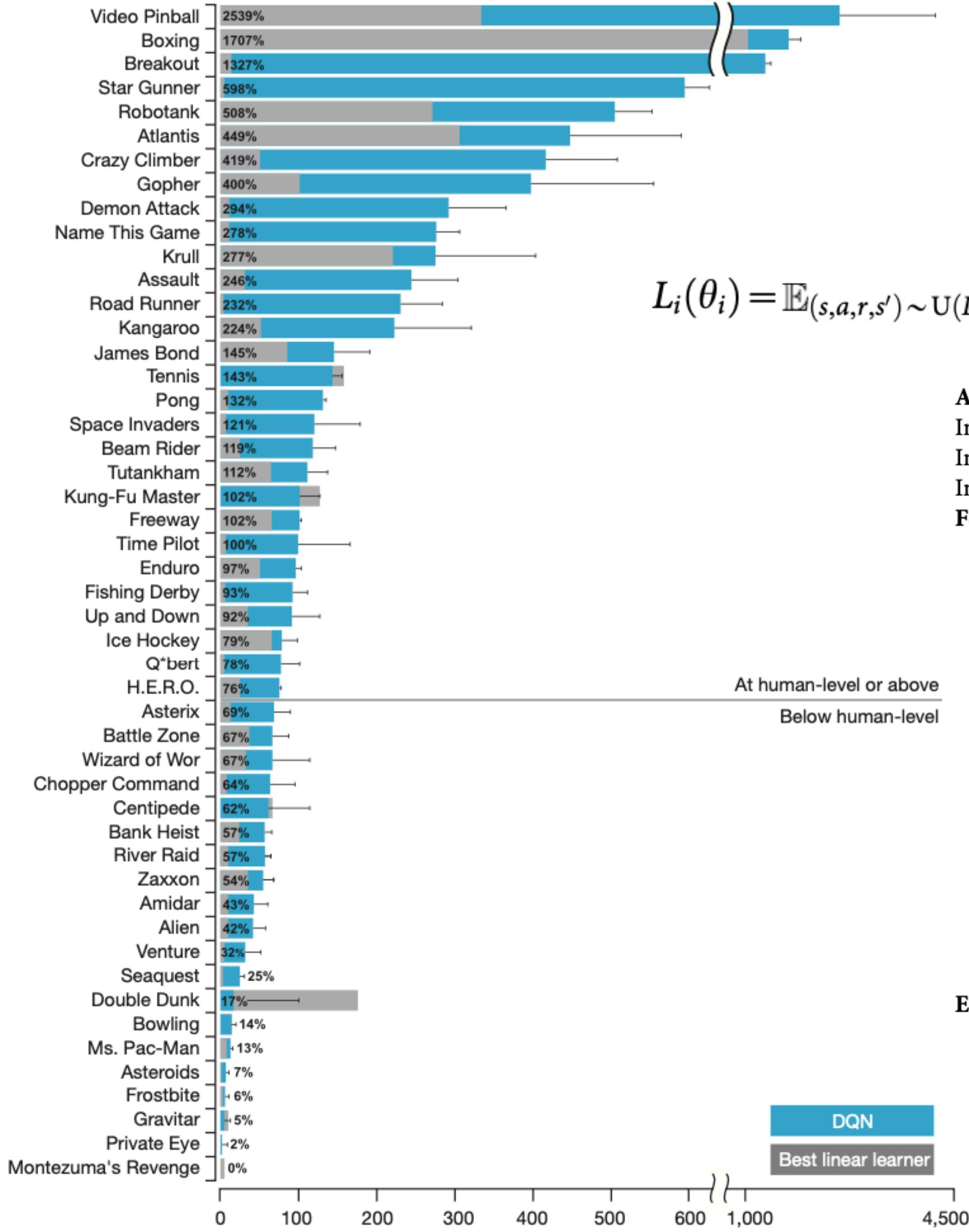
end for



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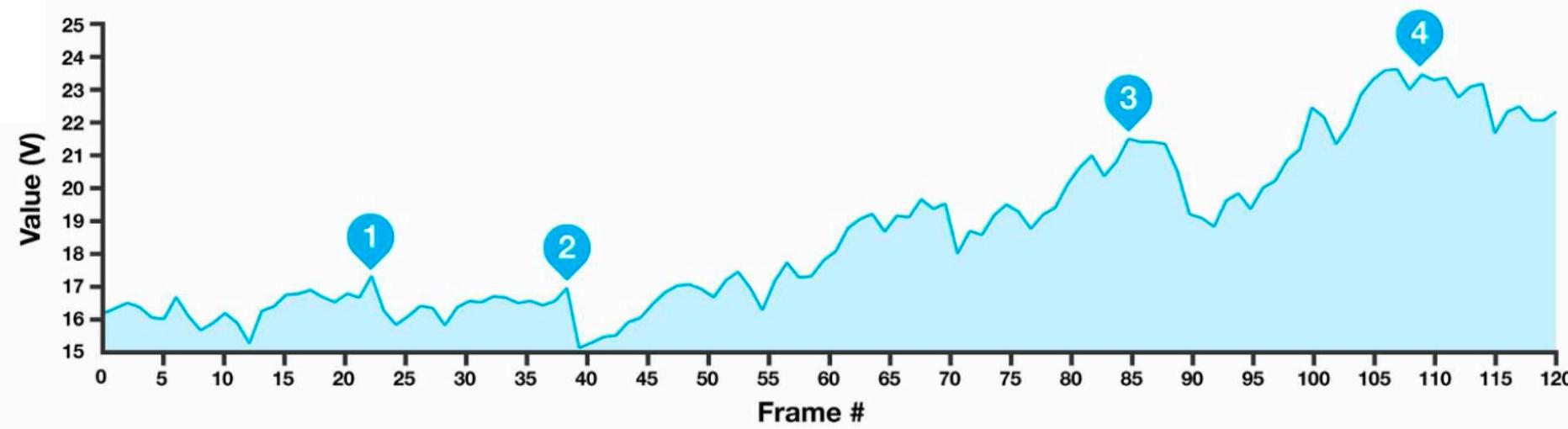
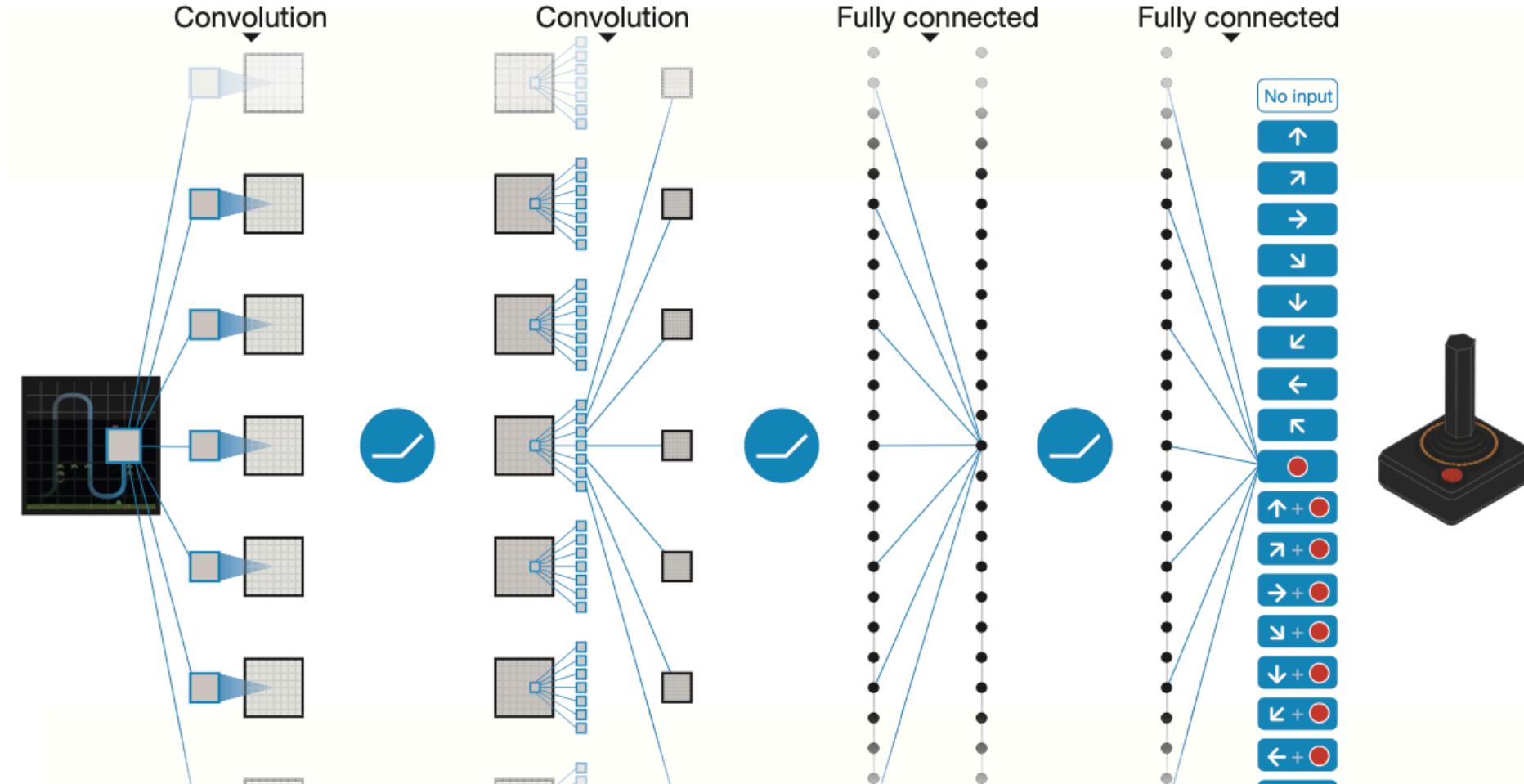
$$L_i(\theta_i) = \mathbb{E}_{(s,a,r,s') \sim U(D)} \left[\left(r + \gamma \max_{a'} Q(s', a'; \theta_i^-) - Q(s, a; \theta_i) \right)^2 \right]$$

Algorithm 1: deep Q-learning with experience replay.

```

Initialize replay memory  $D$  to capacity  $N$ 
Initialize action-value function  $Q$  with random weights  $\theta$ 
Initialize target action-value function  $\hat{Q}$  with weights  $\theta^- = \theta$ 
For episode = 1,  $M$  do
    Initialize sequence  $s_1 = \{x_1\}$  and preprocessed sequence  $\phi_1 = \phi(s_1)$ 
    For  $t = 1, T$  do
        With probability  $\varepsilon$  select a random action  $a_t$ 
        otherwise select  $a_t = \operatorname{argmax}_a Q(\phi(s_t), a; \theta)$ 
        Execute action  $a_t$  in emulator and observe reward  $r_t$  and image  $x_{t+1}$ 
        Set  $s_{t+1} = s_t, a_t, x_{t+1}$  and preprocess  $\phi_{t+1} = \phi(s_{t+1})$ 
        Store transition  $(\phi_t, a_t, r_t, \phi_{t+1})$  in  $D$ 
        Sample random minibatch of transitions  $(\phi_j, a_j, r_j, \phi_{j+1})$  from  $D$ 
        Set  $y_j = \begin{cases} r_j & \text{if episode terminates at step } j+1 \\ r_j + \gamma \max_{a'} \hat{Q}(\phi_{j+1}, a'; \theta^-) & \text{otherwise} \end{cases}$ 
        Perform a gradient descent step on  $(y_j - Q(\phi_j, a_j; \theta))^2$  with respect to the
        network parameters  $\theta$ 
        Every  $C$  steps reset  $\hat{Q} = Q$ 
    End For
End For

```





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Continuous Control with Deep Reinforcement Learning



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human arm \rightarrow 7 degrees of freedom

$$a_i \in \{-k, 0, k\}, i = 1, \dots, 7$$

$3^7 = 2187 \rightarrow$ dimensionality of action space

Background

\mathcal{E} \rightarrow environment (maybe stochastic)

$t \rightarrow$ time step

$x_t \rightarrow$ observation

$a_t \rightarrow$ action

$r_t \rightarrow$ reward

$s_t = x_1, a_1, x_2, a_2, \dots, a_{t-1}, x_t \rightarrow$ state
 ↳ partially observed environment

$s_t = x_t \rightarrow$ fully observed environment

$\pi : \mathcal{S} \rightarrow \mathcal{P}(\mathcal{A})$ set of legal actions
 ↳ states
 policy

$p(s_1) \rightarrow$ initial state distribution

$\{p(s_{t+1}|s_t, a_t)\} \rightarrow$ transition dynamics

$\{r(s_t, a_t)\} \rightarrow$ reward function

MDP: Markov Decision Process

$$R_t = \sum_{i=t}^T \gamma^{i-t} r(s_i, a_i) \rightarrow \text{future discounted return}$$

$$J = \mathbb{E}_{r_i, s_i \sim \mathcal{E}, a_i \sim \pi}[R_1]$$

$\rho^\pi \rightarrow$ discounted state visitation distribution for a policy π

$$Q^\pi(s_t, a_t) = \mathbb{E}_{r_i \geq t, s_i > t \sim \mathcal{E}, a_i > t \sim \pi}[R_t | s_t, a_t]$$

↳ action-value function
 expected return after taking action a_t in state s_t and thereafter following policy π

$$Q^\pi(s_t, a_t) = \mathbb{E}_{r_t, s_{t+1} \sim \mathcal{E}} [r(s_t, a_t) + \gamma \mathbb{E}_{a_{t+1} \sim \pi}[Q^\pi(s_{t+1}, a_{t+1})]]$$

↳ Bellman Equation

↳ if deterministic target policy

$$Q^\pi(s_t, a_t) = \mathbb{E}_{r_t, s_{t+1} \sim \mathcal{E}} [r(s_t, a_t) + \gamma Q^\pi(s_{t+1}, a_{t+1})]$$

It is therefore possible to learn Q^π off-policy

$\beta \rightarrow$ stochastic behavior policy

$$\mu(s) = \arg \max_a Q(s, a) \rightarrow \text{greedy policy}$$

$$L(\theta^Q) = \mathbb{E}_{s_t \sim \rho^\beta, a_t \sim \beta, r_t \sim \mathcal{E}} [(Q(s_t, a_t | \theta^Q) - y_t)^2]$$

$$y_t = r(s_t, a_t) + \gamma Q(s_{t+1}, \mu(s_{t+1}) | \theta^Q)$$

* replay buffer

* separate target network

$\mu(s | \theta^\mu) \rightarrow$ actor function

$Q(s, a) \rightarrow$ critic (Q-Learning & Bellman Equation)

$$\nabla_{\theta^\mu} J \approx \mathbb{E}_{s_t \sim \rho^\beta} [\nabla_{\theta^\mu} Q(s, a | \theta^Q) |_{s=s_t, a=\mu(s_t | \theta^\mu)}]$$

$$= \mathbb{E}_{s_t \sim \rho^\beta} [\nabla_a Q(s, a | \theta^Q) |_{s=s_t, a=\mu(s_t)} \nabla_{\theta^\mu} \mu(s | \theta^\mu) |_{s=s_t}]$$

$$L(\theta^\mu) = -\mathbb{E}_{s_t \sim \rho^\beta} [Q(s_t, \underbrace{\mu(s_t | \theta^\mu)}_{a_t} | \theta^Q)]$$

Deterministic Policy Gradient (DPG) algorithm

Algorithm 1 DDPG algorithm

Randomly initialize critic network $Q(s, a | \theta^Q)$ and actor $\mu(s | \theta^\mu)$ with weights θ^Q and θ^μ .
 Initialize target network Q' and μ' with weights $\theta^{Q'} \leftarrow \theta^Q, \theta^{\mu'} \leftarrow \theta^\mu$
 Initialize replay buffer R
for episode = 1, M **do**
 Initialize a random process \mathcal{N} for action exploration
 Receive initial observation state s_1
for t = 1, T **do**
 Select action $a_t = \mu(s_t | \theta^\mu) + \mathcal{N}_t$ according to the current policy and exploration noise
 Execute action a_t and observe reward r_t and observe new state s_{t+1}
 Store transition (s_t, a_t, r_t, s_{t+1}) in R
 Sample a random minibatch of N transitions (s_i, a_i, r_i, s_{i+1}) from R
 Set $y_i = r_i + \gamma Q'(s_{i+1}, \mu'(s_{i+1} | \theta^{\mu'}) | \theta^{Q'})$
 Update critic by minimizing the loss: $L = \frac{1}{N} \sum_i (y_i - Q(s_i, a_i | \theta^Q))^2$
 Update the actor policy using the sampled policy gradient:

$$\nabla_{\theta^\mu} J \approx \frac{1}{N} \sum_i \nabla_a Q(s, a | \theta^Q) |_{s=s_i, a=\mu(s_i)} \nabla_{\theta^\mu} \mu(s | \theta^\mu) |_{s=s_i}$$

Update the target networks:

$$\begin{aligned} \theta^{Q'} &\leftarrow \tau \theta^Q + (1 - \tau) \theta^{Q'} \\ \theta^{\mu'} &\leftarrow \tau \theta^\mu + (1 - \tau) \theta^{\mu'} \end{aligned}$$

end for
end for

<https://www.youtube.com/watch?v=tJB1qkC1wWM&feature=youtu.be>



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$(\mathcal{S}, \mathcal{A}, P, c, \rho_0, \gamma) \rightarrow$ infinite-horizon discounted Markov Decision Process (MDP)

$\mathcal{S} \rightarrow$ finite set of states

$\mathcal{A} \rightarrow$ finite set of actions

$P \rightarrow$ transition probability distribution

$P : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \rightarrow \mathbb{R}$

$c \rightarrow$ cost function

$c : \mathcal{S} \rightarrow \mathbb{R}$

$\rho_0 \rightarrow$ distribution of initial state s_0

$\rho_0 : \mathcal{S} \rightarrow \mathbb{R}$

$\gamma \in (0, 1) \rightarrow$ discount factor

$\pi \rightarrow$ stochastic policy

$\pi : \mathcal{S} \times \mathcal{A} \rightarrow [0, 1]$

$\eta(\pi) \rightarrow$ expected discounted cost

$\eta(\pi) = \mathbb{E}_{s_0, a_0, \dots} \left[\sum_{t=0}^{\infty} \gamma^t c(s_t) \right]$

$s_0 \sim \rho_0(s_0), a_t \sim \pi(a_t | s_t), s_{t+1} \sim P(s_{t+1} | s_t, a_t)$

$Q_\pi(s_t, a_t) \rightarrow$ state-action value function

$Q_\pi(s_t, a_t) = \mathbb{E}_{s_{t+1}, a_{t+1}, \dots} \left[\sum_{l=0}^{\infty} \gamma^l c(s_{t+l}) \right]$

$V_\pi(s_t) \rightarrow$ value function

$V_\pi(s_t) = \mathbb{E}_{a_t, s_{t+1}, \dots} \left[\sum_{l=0}^{\infty} \gamma^l c(s_{t+l}) \right]$

$A_\pi(s_t, a_t) \rightarrow$ advantage function

$A_\pi(s_t, a_t) = Q_\pi(s_t, a_t) - V_\pi(s_t)$

Trust Region Policy Optimization

$\rho_\pi(s) \rightarrow$ (unnormalized) discounted visitation frequencies

$\rho_\pi(s) = (P(s_0 = s) + \gamma P(s_1 = s) + \gamma^2 P(s_2 = s) + \dots)$

where $s_0 \sim \rho_0$ and the actions are chosen according to π

Algorithm 1 Approximate policy iteration algorithm guaranteeing non-increasing expected cost η

Initialize π_0 . See the paper for proof!

for $i = 0, 1, 2, \dots$ until convergence **do**

 Compute all advantage values $A_{\pi_i}(s, a)$.

 Solve the constrained optimization problem

$$\pi_{i+1} = \arg \min_{\pi} \left[L_{\pi_i}(\pi) + \underbrace{\left(\frac{2\epsilon\gamma}{(1-\gamma)^2} \right)}_{C} D_{\text{KL}}^{\max}(\pi_i, \pi) \right]$$

 where $\epsilon = \max_s \max_a |A_\pi(s, a)|$

 and $L_{\pi_i}(\pi) = \eta(\pi_i) + \sum_s \rho_{\pi_i}(s) \sum_a \pi(a|s) A_{\pi_i}(s, a)$

end for $D_{\text{KL}}^{\max}(\pi, \tilde{\pi}) = \max_s D_{\text{KL}}(\pi(\cdot|s) \parallel \tilde{\pi}(\cdot|s))$

In practice, if we used the penalty coefficient C above recommended by the theory, the step sizes would be very small.

$\eta(\theta) := \eta(\pi_\theta)$

$L_\theta(\tilde{\theta}) := L_{\pi_\theta}(\pi_{\tilde{\theta}})$, and $D_{\text{KL}}(\theta \parallel \tilde{\theta}) := D_{\text{KL}}(\pi_\theta \parallel \pi_{\tilde{\theta}})$

$\overline{D}_{\text{KL}}^\rho(\theta_1, \theta_2) := \mathbb{E}_{s \sim \rho} [D_{\text{KL}}(\pi_{\theta_1}(\cdot|s) \parallel \pi_{\theta_2}(\cdot|s))]$

$\underset{\theta}{\text{minimize}} L_{\theta_{\text{old}}}(\theta)$ trust region constraint

subject to $\overline{D}_{\text{KL}}^{\rho_{\theta_{\text{old}}}}(\theta_{\text{old}}, \theta) \leq \delta$.

$\underset{\theta}{\text{minimize}} \sum_s \rho_{\theta_{\text{old}}}(s) \sum_a \pi_\theta(a|s) A_{\theta_{\text{old}}}(s, a)$

subject to $\overline{D}_{\text{KL}}^{\rho_{\theta_{\text{old}}}}(\theta_{\text{old}}, \theta) \leq \delta$.

$\sum_s \rho_{\theta_{\text{old}}}(s) [\dots] = \frac{1}{1-\gamma} \mathbb{E}_{s \sim \rho_{\theta_{\text{old}}}} [\dots]$

$\sum_a \pi_\theta(a|s_n) A_{\theta_{\text{old}}}(s_n, a) =$

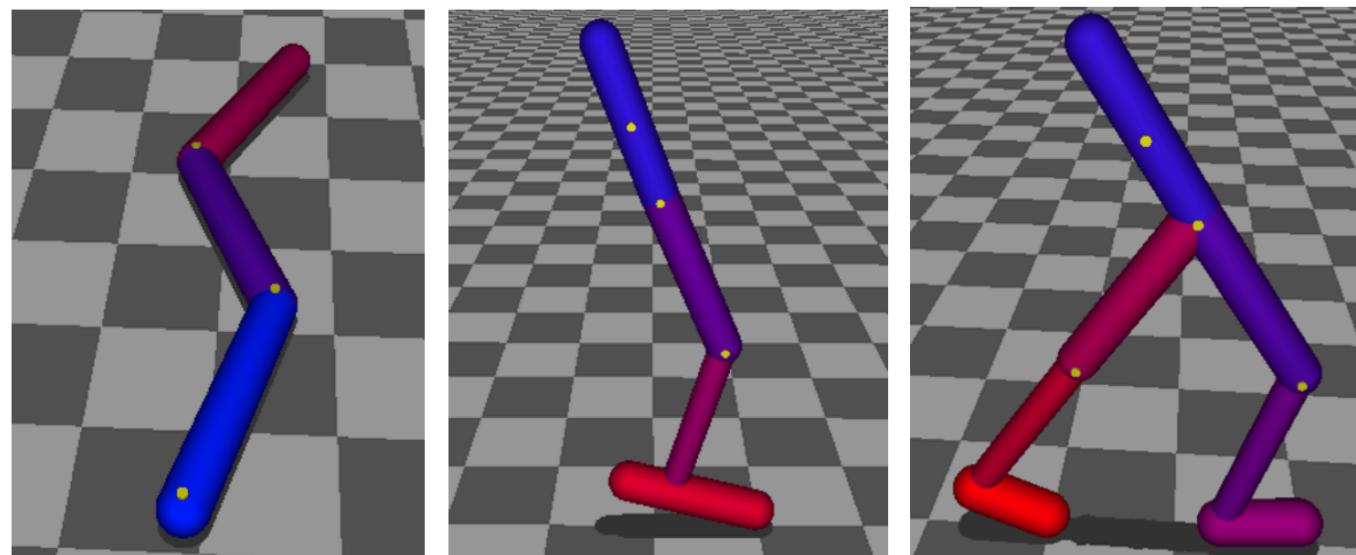
importance sampling $\mathbb{E}_{a \sim q} \left[\frac{\pi_\theta(a|s_n)}{q(a|s_n)} A_{\theta_{\text{old}}}(s_n, a) \right]$

Replace advantage values by Q-values which only changes the objective by a constant.

$\underset{\theta}{\text{minimize}} \mathbb{E}_{s \sim \rho_{\theta_{\text{old}}}, a \sim q} \left[\frac{\pi_\theta(a|s)}{q(a|s)} Q_{\theta_{\text{old}}}(s, a) \right]$

subject to $\mathbb{E}_{s \sim \rho_{\theta_{\text{old}}}} [D_{\text{KL}}(\pi_{\theta_{\text{old}}}(\cdot|s) \parallel \pi_\theta(\cdot|s))] \leq \delta$.

$q(a|s) = \pi_{\theta_{\text{old}}}(a|s)$ TRPO





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Conjugate Gradient Method

TRPO objective function

$$\pi_{k+1} = \arg \max_{\pi'} \mathcal{L}_{\pi_k}(\pi') \text{ s.t. } \bar{D}_{KL}(\pi' || \pi_k) \leq \delta$$

$$\mathcal{L}_{\theta_k}(\theta) \approx g^T (\theta - \theta_k)$$

$$\bar{D}_{KL}(\theta || \theta_k) \approx \frac{1}{2} (\theta - \theta_k)^T H (\theta - \theta_k)$$

$$\arg \min_x f(x) = \frac{1}{2} x^T H x - x^T g$$

$$\nabla f(x) = Hx - g$$

Conjugate gradient method

$$r_0 = g - Hx_0 = -\nabla f(x_0)$$

$$p_0 = r_0$$

$$x_1 = x_0 + \alpha_0 p_0$$

$$f(x_1) = f(x_0 + \alpha_0 p_0) =: g(\alpha_0)$$

$$g'(\alpha_0) = 0 \implies \alpha_0 = \frac{p_0^T (g - Hx_0)}{p_0^T H p_0}$$

$$r_1 = g - Hx_1 = -\nabla f(x_1)$$

$$p_1 = r_1 - \frac{p_0^T H r_1}{p_0^T H p_0} p_0 \rightarrow \text{Gram-Schmidt orthonormalization}$$

$$p_0^T H p_1 = p_0^T H r_1 - \frac{p_0^T H r_1}{p_0^T H p_0} p_0^T H p_0 = 0$$

$\implies p_0$ and p_1 are conjugate w.r.t. H .

$$x_2 = x_1 + \alpha_1 p_1$$

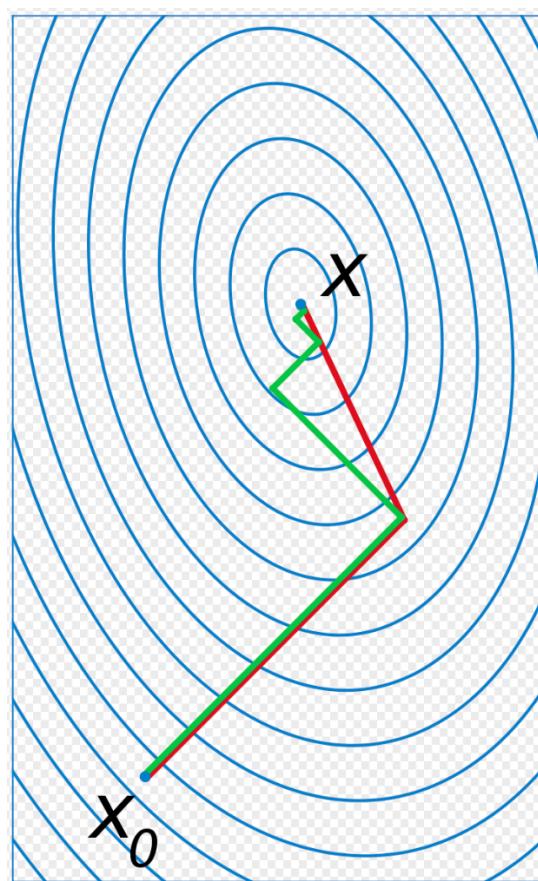
$$\alpha_1 = \frac{p_1^T (g - Hx_1)}{p_1^T H p_1}$$

Linear Approximation

$$\mathcal{L}_{\theta_k}(\theta) \approx \mathcal{L}_{\theta_k}(\theta_k) + g^T (\theta - \theta_k)$$

$$g \doteq \nabla_{\theta} \mathcal{L}_{\theta_k}(\theta) |_{\theta_k}$$

$$H \doteq \nabla_{\theta}^2 \bar{D}_{KL}(\theta || \theta_k) |_{\theta_k}$$



Quadratic Approximation

$$\bar{D}_{KL}(\theta || \theta_k) \approx \bar{D}_{KL}(\theta_k || \theta_k) + \nabla_{\theta} \bar{D}_{KL}(\theta || \theta_k) |_{\theta_k} (\theta - \theta_k) + \frac{1}{2} (\theta - \theta_k)^T H (\theta - \theta_k)$$

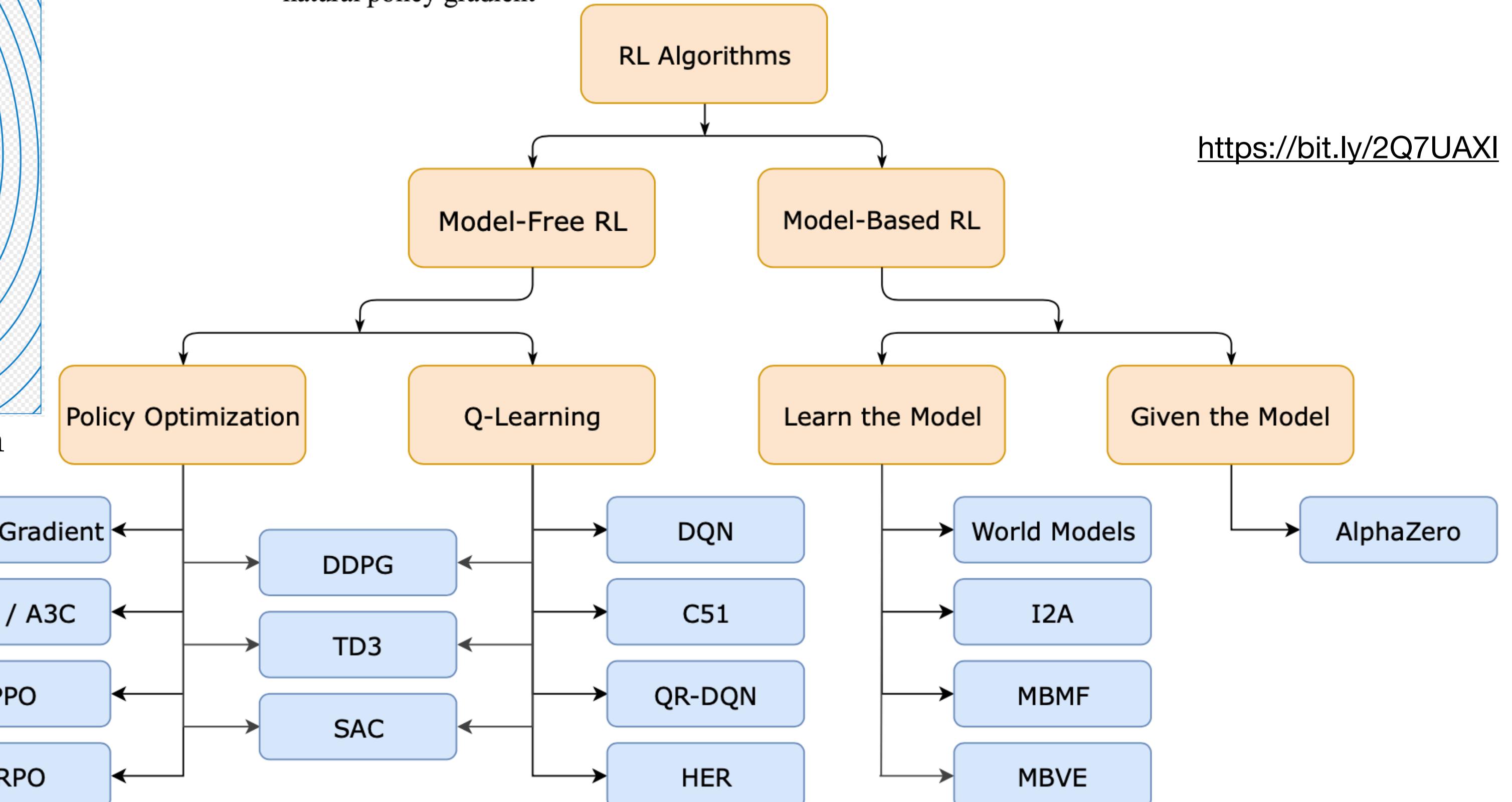
$$\theta_{k+1} = \arg \max_{\theta} g^T (\theta - \theta_k) \text{ s.t. } \frac{1}{2} (\theta - \theta_k)^T H (\theta - \theta_k) \leq \delta$$

$$H^{-1} g = x \implies Hx = g$$

$$Hx = \nabla_{\theta} \left((\nabla_{\theta} \bar{D}_{KL}(\theta || \theta_k))^T x \right)$$

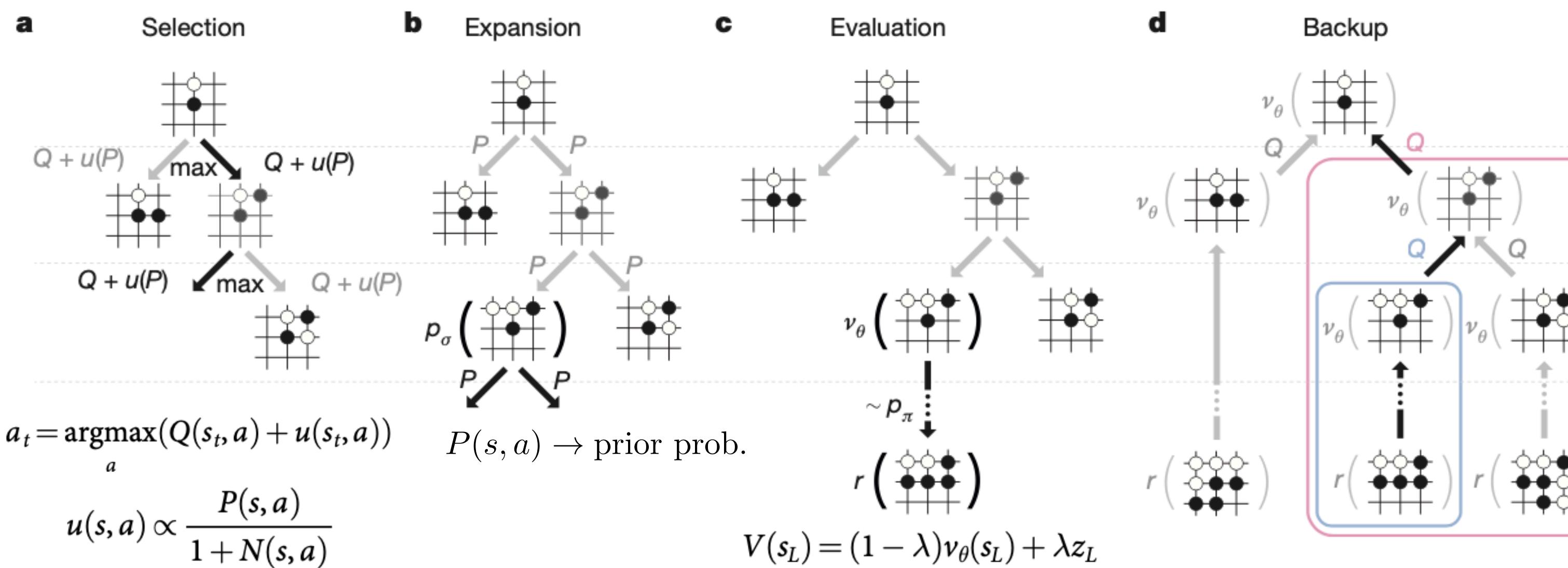
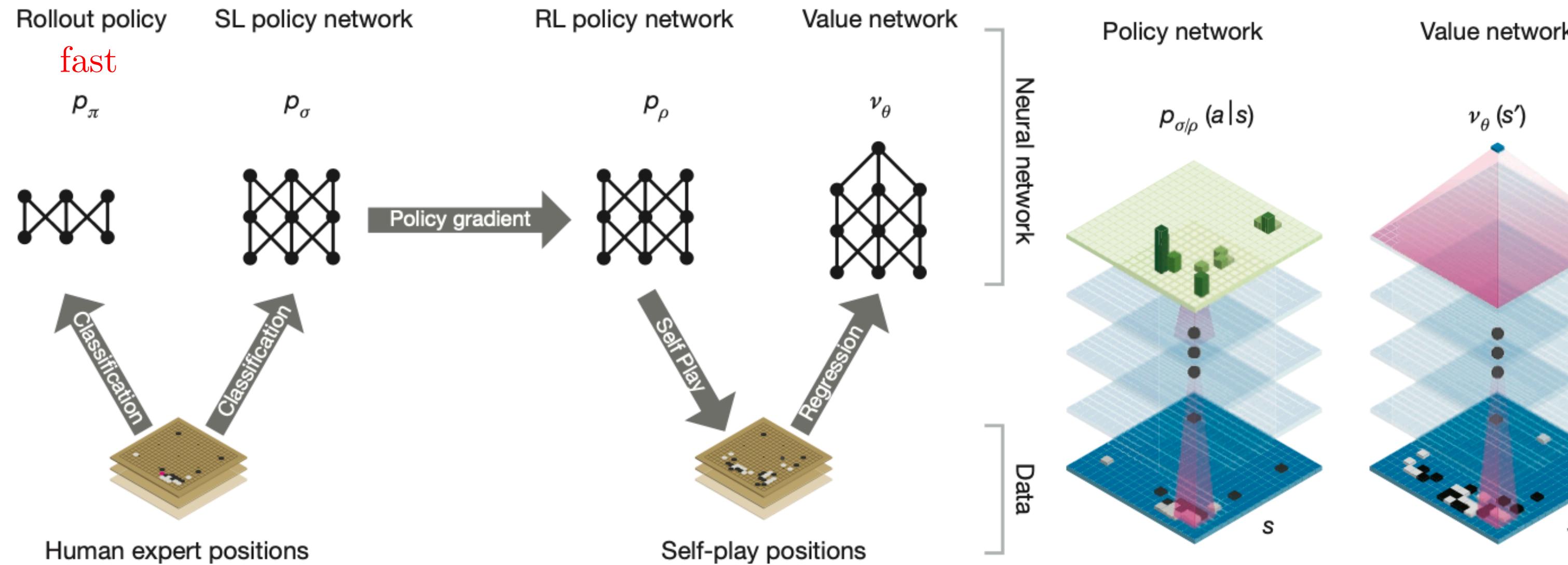
$$\theta_{k+1} = \theta_k + \sqrt{\frac{2\delta}{g^T H^{-1} g}} H^{-1} g$$

natural policy gradient



<https://bit.ly/2Q7UAXI>

Mastering the game of Go with deep neural networks and tree search


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Supervised learning of policy networks

$$\Delta \sigma \propto \frac{\partial \log p_\sigma(a|s)}{\partial \sigma} \rightarrow \text{stochastic gradient ascent (likelihood)}$$

Reinforcement learning of policy networks

$$\Delta \rho \propto \frac{\partial \log p_\rho(a_t|s_t)}{\partial \rho} z_t \rightarrow \text{stochastic gradient ascent (expected outcome)}$$

policy gradient reinforcement learning

$$\Delta \rho \propto \frac{\partial \log p_\rho(a_t|s_t)}{\partial \rho} (z_t - v(s_t)) \rightarrow \text{REINFORCE}$$

variance reduction

$$z_t = \sum_{t'=t+1}^T r_{t'} = r_T \text{ since } r_{t'} = 0 \text{ for } t' < T$$

<https://bit.ly/31OImVQ>

<https://bit.ly/2RCWHn1>

Reinforcement learning of value networks

$$\Delta \theta \propto \frac{\partial v_\theta(s)}{\partial \theta} (z - v_\theta(s)) \rightarrow \text{stochastic gradient descent (MSE: mean squared error)}$$

Monte Carlo tree search (MCTS)

$$N(s, a) = \sum_{i=1}^n 1(s, a, i) \rightarrow \text{visit count}$$

$$Q(s, a) = \frac{1}{N(s, a)} \sum_{i=1}^n 1(s, a, i) V(s_L^i) \rightarrow \text{action value}$$



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Asynchronous Methods for Deep Reinforcement Learning



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value-based model-free methods

$Q(s, a; \theta) \rightarrow$ approximate action-value function

$Q^*(s, a) \approx Q(s, a; \theta) \rightarrow$ Q-Learning

$$L_i(\theta_i) = \mathbb{E}[(r + \gamma \max_{a'} Q(s', a'; \theta_{i-1}) - Q(s, a; \theta_i))^2]$$

one-step return

$$r_t + \gamma r_{t+1} + \dots + \gamma^{n-1} r_{t+n-1} + \max_a \gamma^n Q(s_{t+n}, a)$$

n-step return

A single reward directly affects the values of n preceding state action pairs

policy-based model-free methods

$$\pi(a|s; \theta)$$

gradient ascent on $\mathbb{E}[R_t]$

$$\underbrace{\nabla_\theta \log \pi(a_t|s_t; \theta) R_t}_{\text{as an unbiased estimate of } \nabla_\theta \mathbb{E}[R_t]} \rightarrow \text{REINFORCE}$$

as an unbiased estimate of $\nabla_\theta \mathbb{E}[R_t]$

$$\nabla_\theta \log \pi(a_t|s_t; \theta) (R_t - \underbrace{b_t(s_t)}_{\text{baseline}})$$

$$b_t(s_t) \approx V^\pi(s_t)$$

$R_t - b_t \approx$ advantage of action a_t in state s_t

$$A(a_t, s_t) = \underbrace{Q(a_t, s_t)}_{\approx R_t} - \underbrace{V(s_t)}_{\approx b_t}$$

$\underbrace{\pi}_{\text{actor}} - \underbrace{b}_{\text{critic}}$

Mnih, Volodymyr, et al. "Asynchronous methods for deep reinforcement learning." *International conference on machine learning*. 2016.

Asynchronous Advantage Actor-Critic (A3C)

Algorithm Asynchronous advantage actor-critic - pseudocode for each actor-learner thread.

// Assume global shared parameter vectors θ and θ_v , and global shared counter $T = 0$

// Assume thread-specific parameter vectors θ' and θ'_v

Initialize thread step counter $t \leftarrow 1$

<https://www.youtube.com/watch?v=0xo1Ldx3L5Q&feature=youtu.be>

repeat

 Reset gradients: $d\theta \leftarrow 0$ and $d\theta_v \leftarrow 0$.

 Synchronize thread-specific parameters $\theta' = \theta$ and $\theta'_v = \theta_v$

$t_{start} = t$

 Get state s_t

<https://www.youtube.com/watch?v=Ajjc08-iPx8&feature=youtu.be>

repeat

 Perform a_t according to policy $\pi(a_t|s_t; \theta')$

 Receive reward r_t and new state s_{t+1}

$t \leftarrow t + 1$

$T \leftarrow T + 1$

<https://www.youtube.com/watch?v=nMR5mjCFZCw&feature=youtu.be>

until terminal s_t **or** $t - t_{start} == t_{max}$

$$R = \begin{cases} 0 & \text{for terminal } s_t \\ V(s_t, \theta'_v) & \text{for non-terminal } s_t // \text{Bootstrap from last state} \end{cases}$$

for $i \in \{t - 1, \dots, t_{start}\}$ **do**

$$R \leftarrow r_i + \gamma R$$

Accumulate gradients wrt θ' : $d\theta \leftarrow d\theta + \nabla_{\theta'} \log \pi(a_i|s_i; \theta') (R - V(s_i; \theta'_v))$

Accumulate gradients wrt θ'_v : $d\theta_v \leftarrow d\theta_v + \partial (R - V(s_i; \theta'_v))^2 / \partial \theta'_v$

end for

Perform asynchronous update of θ using $d\theta$ and of θ_v using $d\theta_v$.

until $T > T_{max}$

$$\nabla_\theta \log \pi(a_t|s_t; \theta) + \underbrace{A(s_t, a_t; \theta, \theta_v)}_{\sum_{i=0}^{k-1} \gamma^i r_{t+i} + \gamma^k V(s_{t+k}; \theta_v) - V(s_t; \theta_v)} + \beta \nabla_\theta \underbrace{H(\pi(s_t; \theta))}_{\text{entropy}}$$

Dropout as a Bayesian Approximation: Representing Model Uncertainty in Deep Learning


[YouTube Video](#)

$$p(y|x, W^1, W^2) = \text{softmax}(W^2 \text{ReLU}(W^1 x))$$

$$x \in \mathbb{R}^{d_0}, W^1 \in \mathbb{R}^{d_1 \times d_0}, W^2 \in \mathbb{R}^{d_2 \times d_1}$$

$$p(W^1) = \mathcal{N}(0, I), p(W^2) = \mathcal{N}(0, I)$$

$$p(y^*|x^*, \mathcal{D}) = \int p(y^*|x^*, W^1, W^2) \underbrace{p(W^1, W^2|\mathcal{D})}_{\text{not tractable}} dW^1 dW^2$$

$\mathcal{D} \rightarrow$ dataset

$$KL[q(W^1, W^2)||p(W^1, W^2|\mathcal{D})] \leq KL[q(W^1, W^2)||p(W^1)p(W^2)] - \sum_{n=1}^N \int q(W^1, W^2) \log p(y_n|x_n, W^1, W^2)$$

$$q(W^1, W^2) = q(W^1)q(W^2) \rightarrow \text{Variational Distribution}$$

$$q(W^\ell) = p^\ell \mathcal{N}(M^\ell, \sigma^2 I) + (1 - p^\ell) \mathcal{N}(0, \sigma^2 I) \rightarrow \text{Gaussian mixture distribution}$$

$$KL[q(W^\ell)||p(W^\ell)] \approx d^{\ell-1} d^\ell (\sigma^2 - \log(\sigma^2) - 1) + \frac{p^\ell}{2} \|W^\ell\|_2^2 + \text{constant}$$

$$\sigma = 10^{-33} \implies \log(\sigma) = -76$$

$$W^\ell \approx \text{diag}(z^\ell) M^\ell, M^\ell \in \mathbb{R}^{d_\ell \times d_{\ell-1}}, z^\ell \sim \text{Bernoulli}(p^\ell)$$

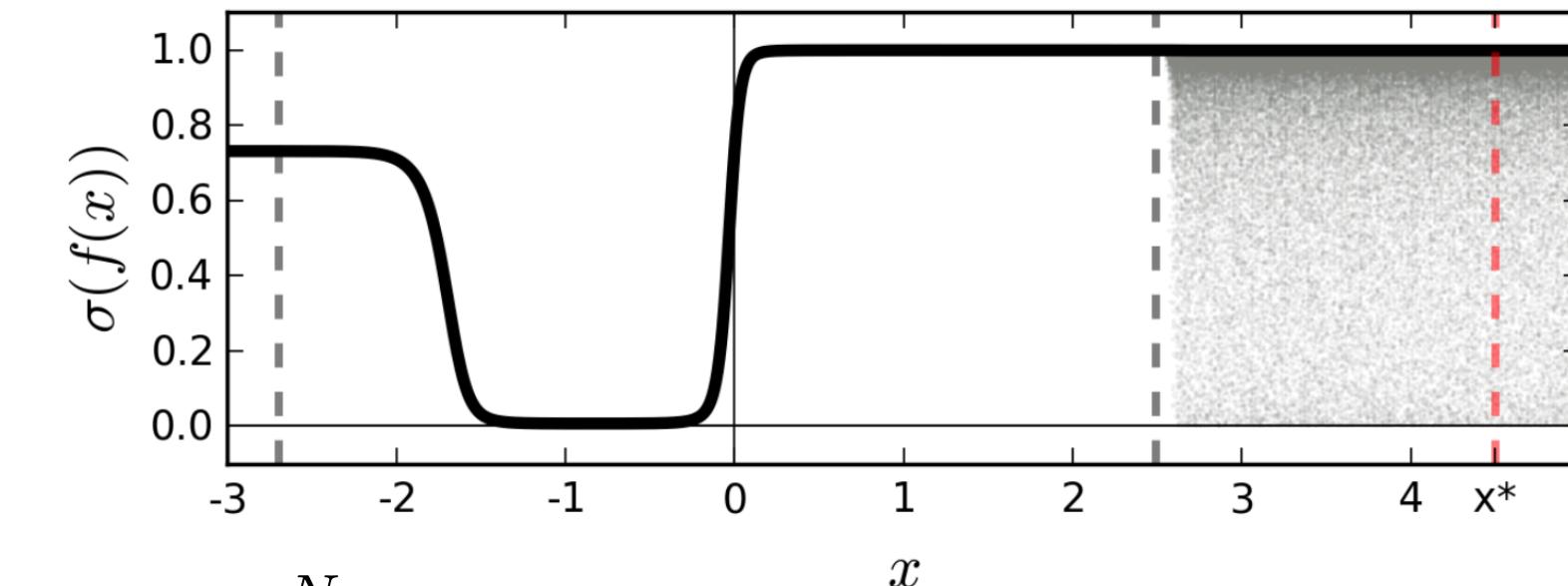
$$KL[q(W^1, W^2)||p(W^1, W^2|\mathcal{D})] \leq - \sum_{n=1}^N \log p(y_n|x_n, W_n^1, W_n^2) + \frac{p^1}{2} \|M_1\|_2^2 + \frac{p^2}{2} \|M_2\|_2^2$$

$$W_n^\ell \approx \text{diag}(z_n^\ell) M^\ell \rightarrow \text{Monte Carlo}$$

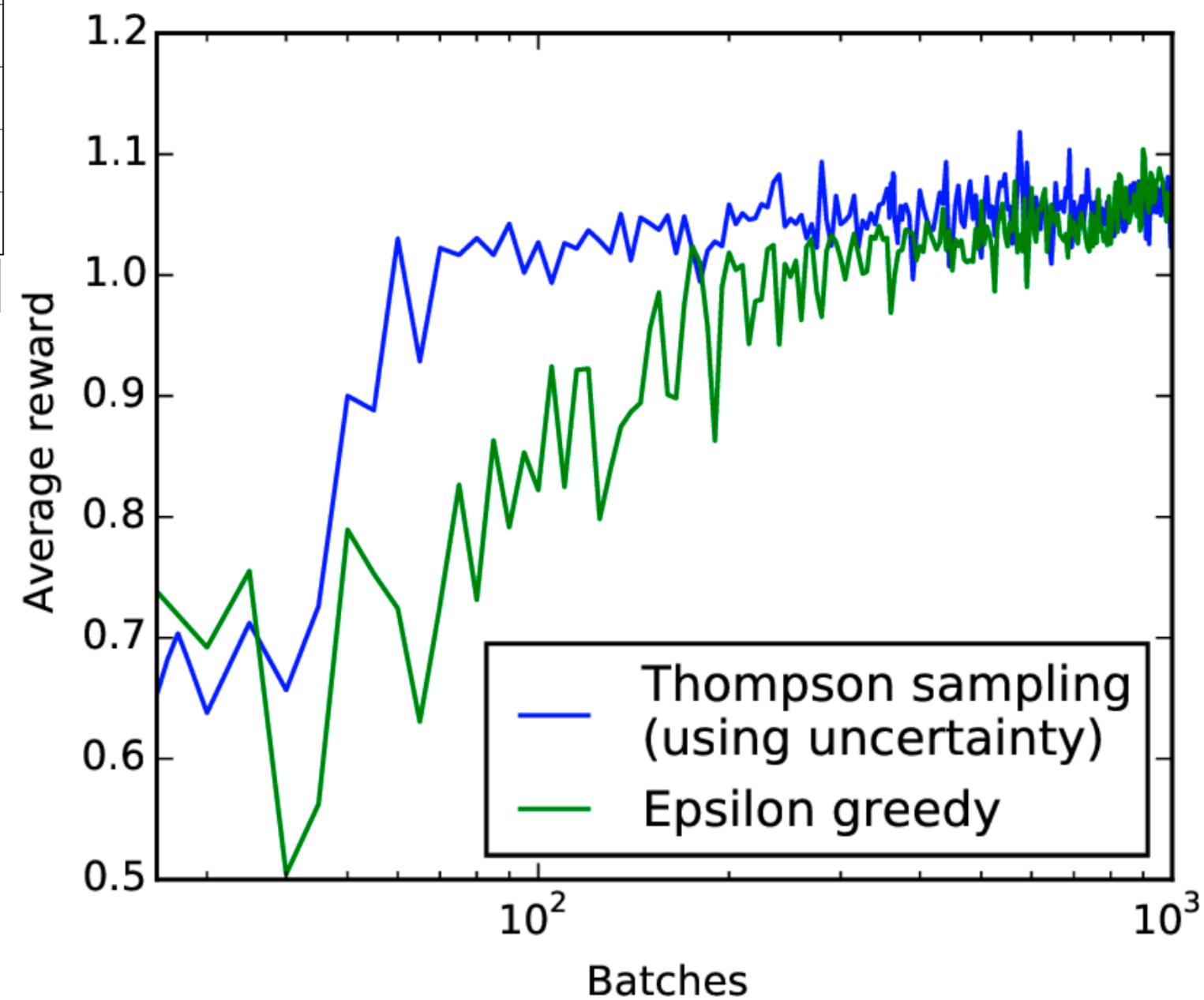
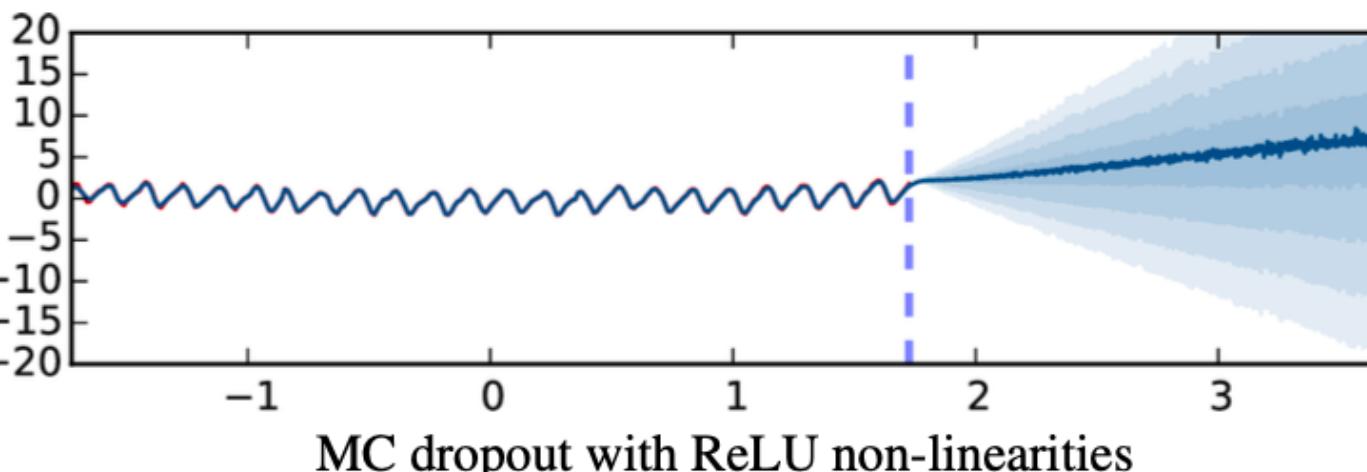
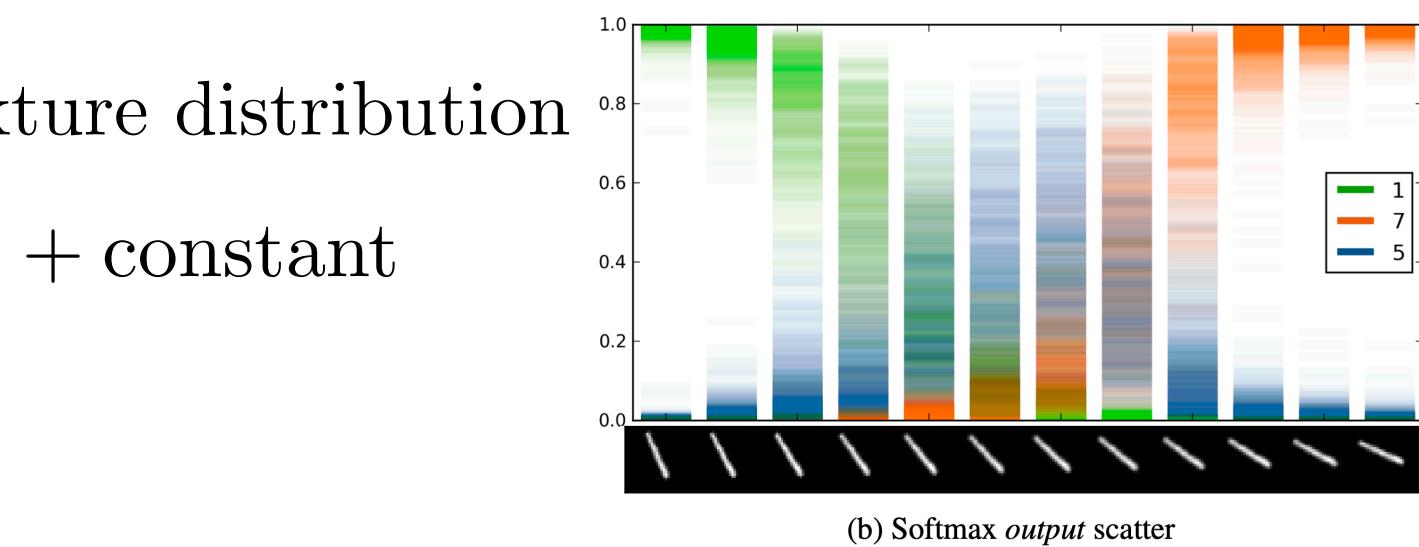
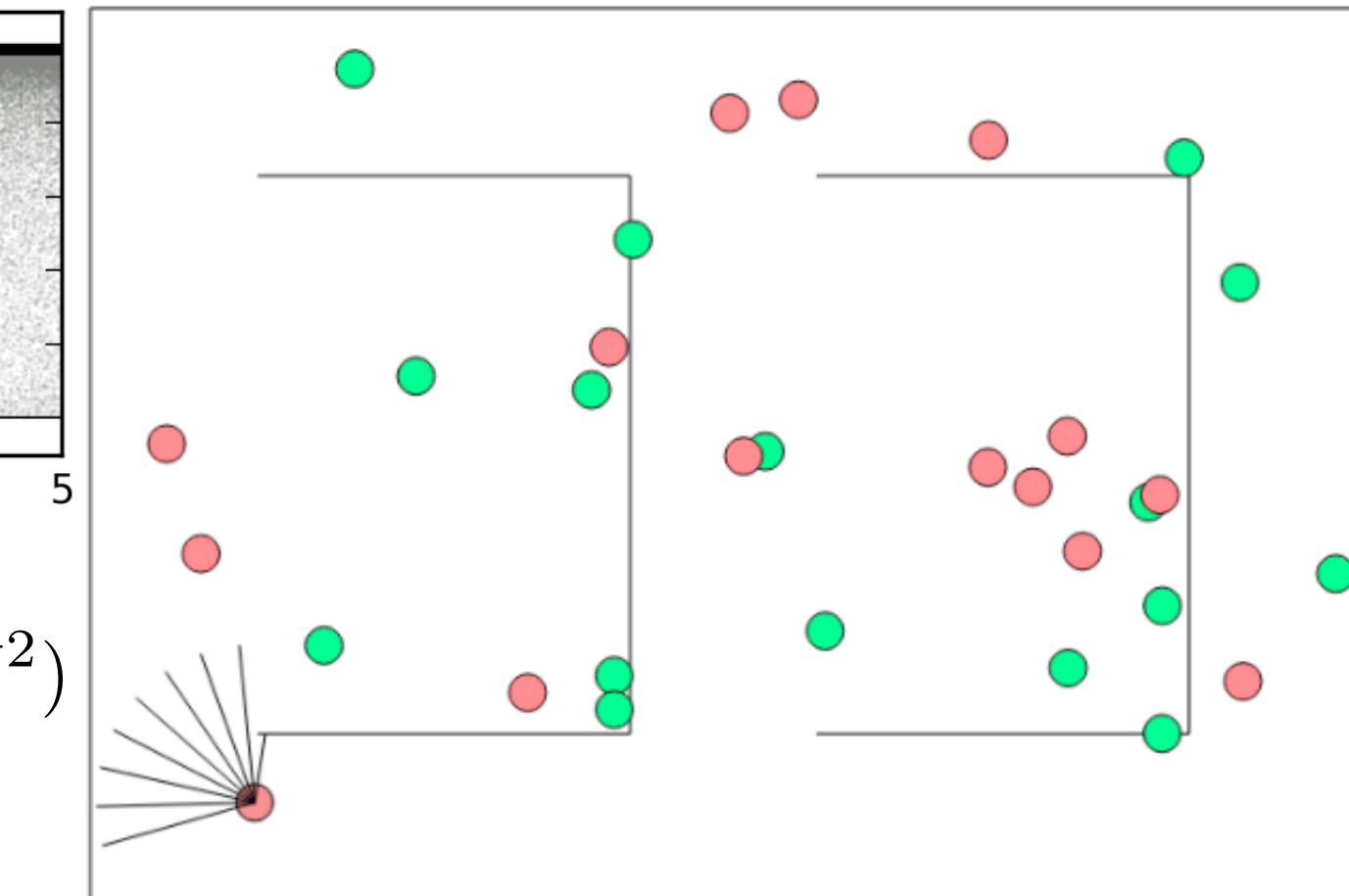
Same loss as the one used by dropout!

$$p(y^*|x^*, \mathcal{D}) \approx \int p(y^*|x^*, W^1, W^2) q(W^1) q(W^2) dW^1 dW^2$$

Use Monte Carlo to obtain the mean and variance of the predictions!



$$\sum_{n=1}^N \int q(W^1, W^2) \log p(y_n|x_n, W^1, W^2)$$





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Deep Reinforcement Learning with Double Q-Learning

$$V^*(s) = \max_a \sum_{s'} T(s, a, s') [R(s, a, s') + \gamma V^*(s')]$$

Bellman Optimality Equation

$$V_{k+1}(s) = \max_a \sum_{s'} T(s, a, s') [R(s, a, s') + \gamma V_k(s')]$$

Value Iteration Algorithm

$$Q_{k+1}(s, a) = \sum_{s'} T(s, a, s') [R(s, a, s') + \gamma \max_{s'} Q_k(s', a')]$$

Q-Value Iteration Algorithm

$$V_{k+1}(s) = (1 - \alpha)V_k(s) + \alpha(r + \gamma V_k(s'))$$

$$= V_k(s) + \underbrace{\alpha(r + \gamma V_k(s') - V_k(s))}_{\delta_k(s, r, s')}$$

Temporal Difference Learning

$$Q_{k+1}(s, a) = (1 - \alpha)Q_k(s, a) + \alpha(r + \gamma \max_{a'} Q_k(s', a'))$$

$$= Q_k(s, a) + \alpha(r + \gamma \max_{a'} Q_k(s', a') - Q_k(s, a))$$

Q-Learning

Q-Learning is a form of Temporal Difference Learning

Q-Learning overestimates action values

$$Q_\pi(s, a) \equiv \mathbb{E}[R_1 + \gamma R_2 + \dots | S_0 = s, A_0 = a, \pi]$$

$$Q_*(s, a) = \max_\pi Q_\pi(s, a)$$

$$Q(s, a; \theta_t)$$

$$\theta_{t+1} = \theta_t + \alpha(Y_t^Q - Q(S_t, A_t; \theta_t)) \nabla_{\theta_t} Q(S_t, A_t; \theta_t)$$

$$Y_t^Q \equiv R_{t+1} + \gamma \max_a Q(S_{t+1}, a; \theta_t)$$

$$Q(S_t, A_t; \theta_{t+1}) \approx Q(S_t, A_t; \theta_t) + \alpha(Y_t^Q - Q(S_t, A_t; \theta_t)) \|\nabla_{\theta_t} Q(S_t, A_t; \theta_t)\|^2$$

Taylor Series Expansion

Deep Q Networks

* target network

$$Y_t^{DQN} \equiv R_{t+1} + \gamma \max_a Q(S_{t+1}, a; \theta_t^-)$$

* experience replay

Double Q-Learning

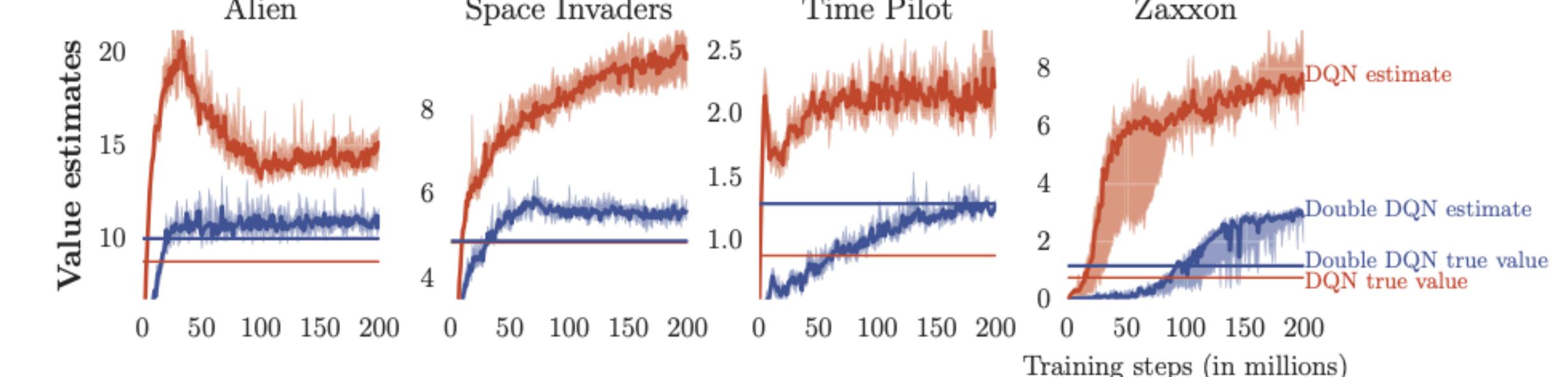
* decouple selection from evaluation

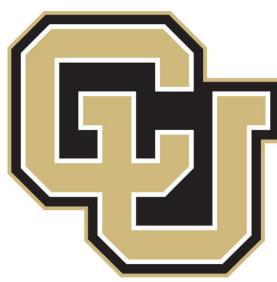
$$Y_t^Q = R_{t+1} + \gamma Q(S_{t+1}, \arg \max_a Q(S_{t+1}, a; \theta_t); \theta_t)$$

$$Y_t^{DoubleQ} \equiv R_{t+1} + \gamma Q(S_{t+1}, \arg \max_a Q(S_{t+1}, a; \theta_t'); \theta_t') \rightarrow \text{two value functions}$$

Double DQN

$$Y_t^{DoubleDQN} \equiv R_{t+1} + \gamma Q(S_{t+1}, \arg \max_a Q(S_{t+1}, a; \theta_t); \theta_t^-) \rightarrow \text{target network}$$





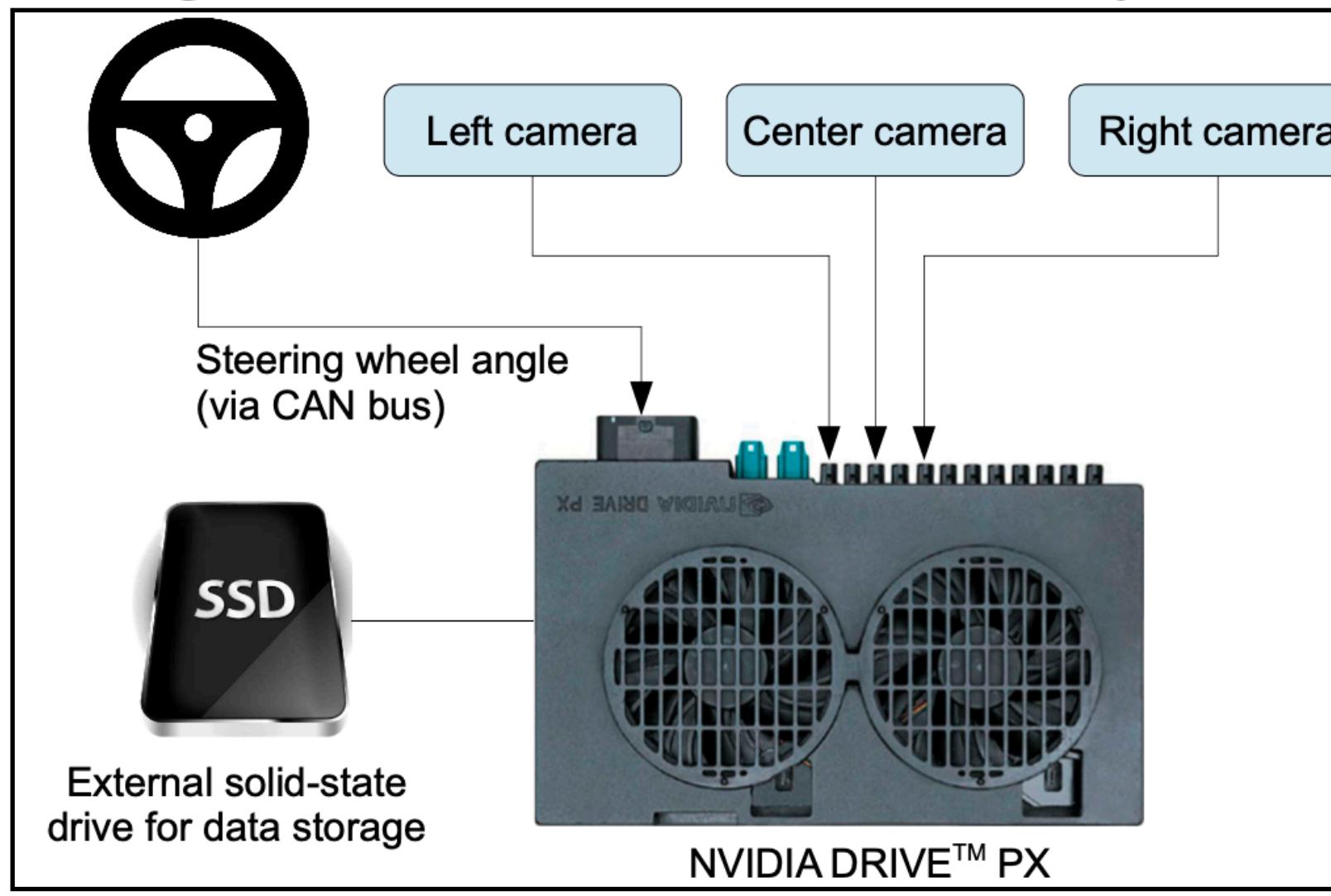
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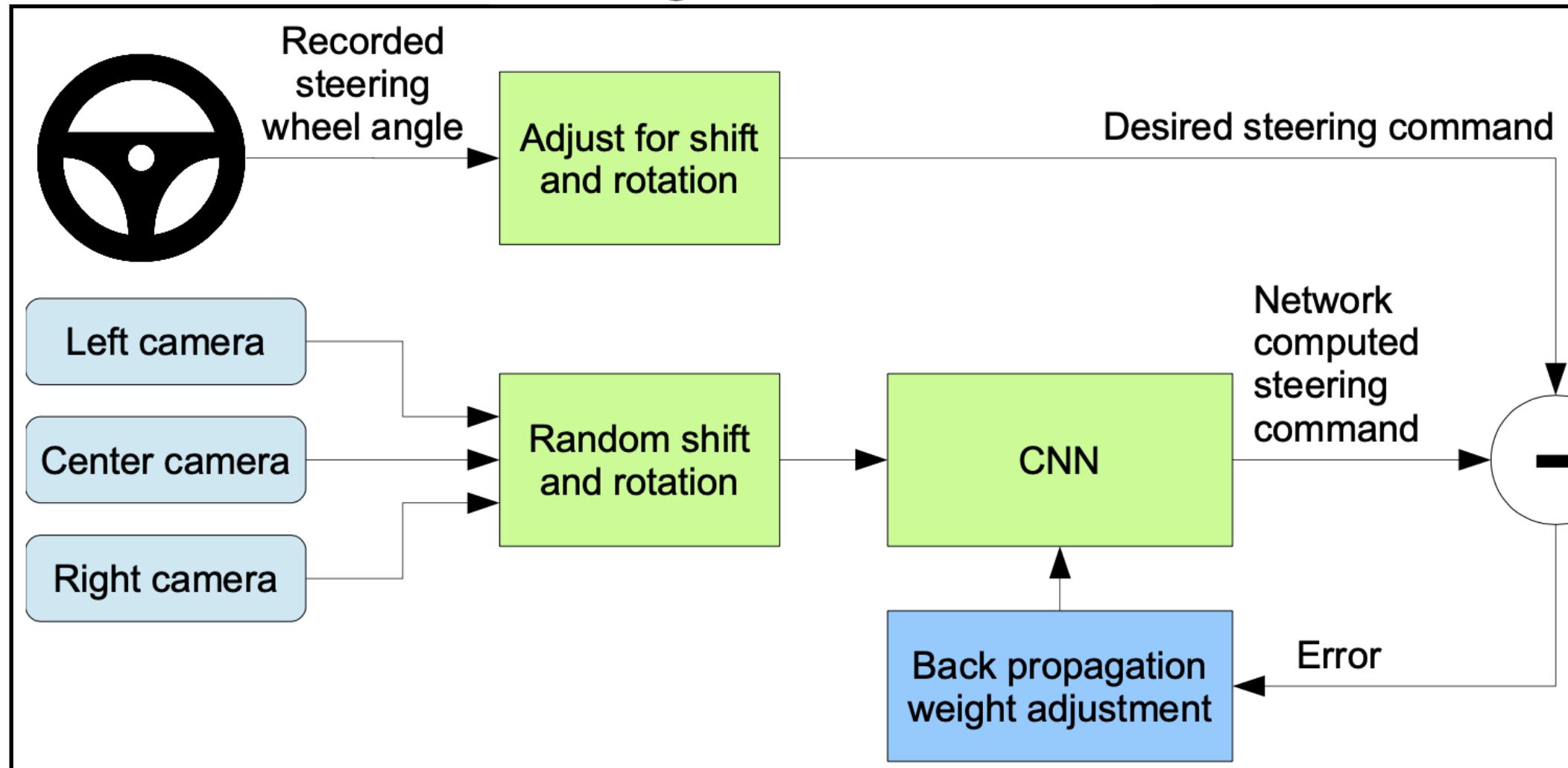
[YouTube Video](#)

End to End Learning for Self-Driving Cars

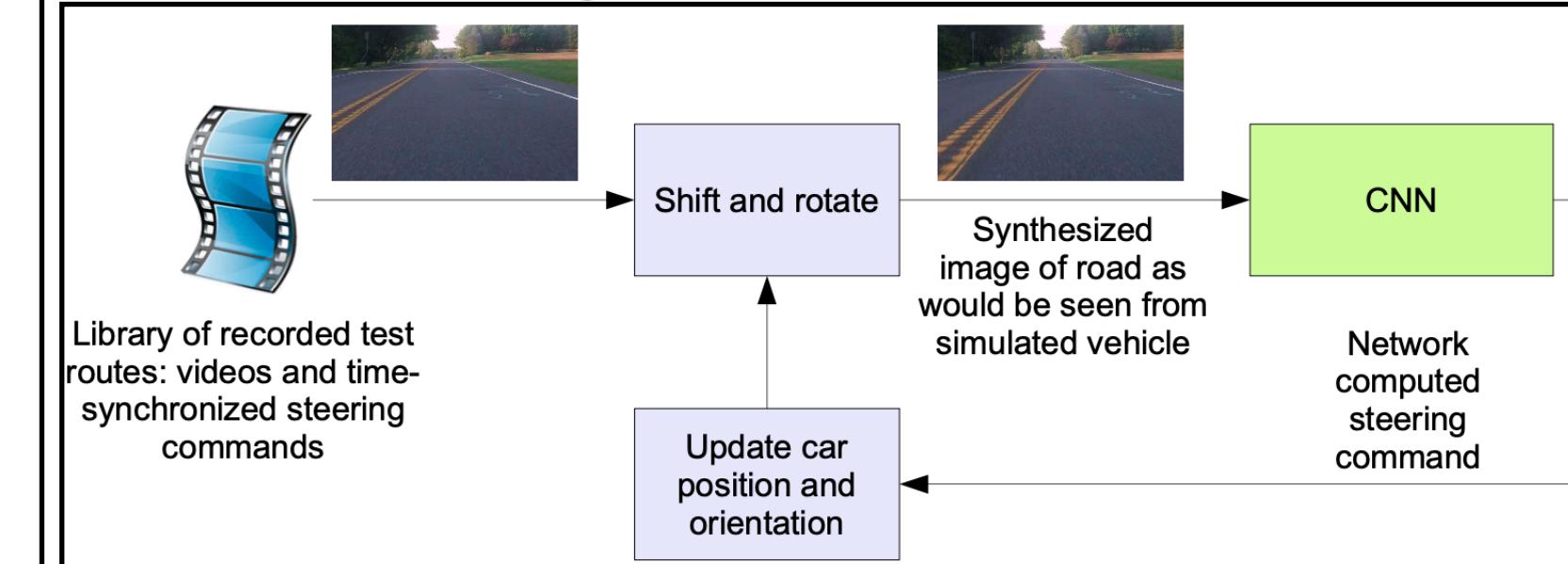
High-level view of the data collection system.



Training the neural network.

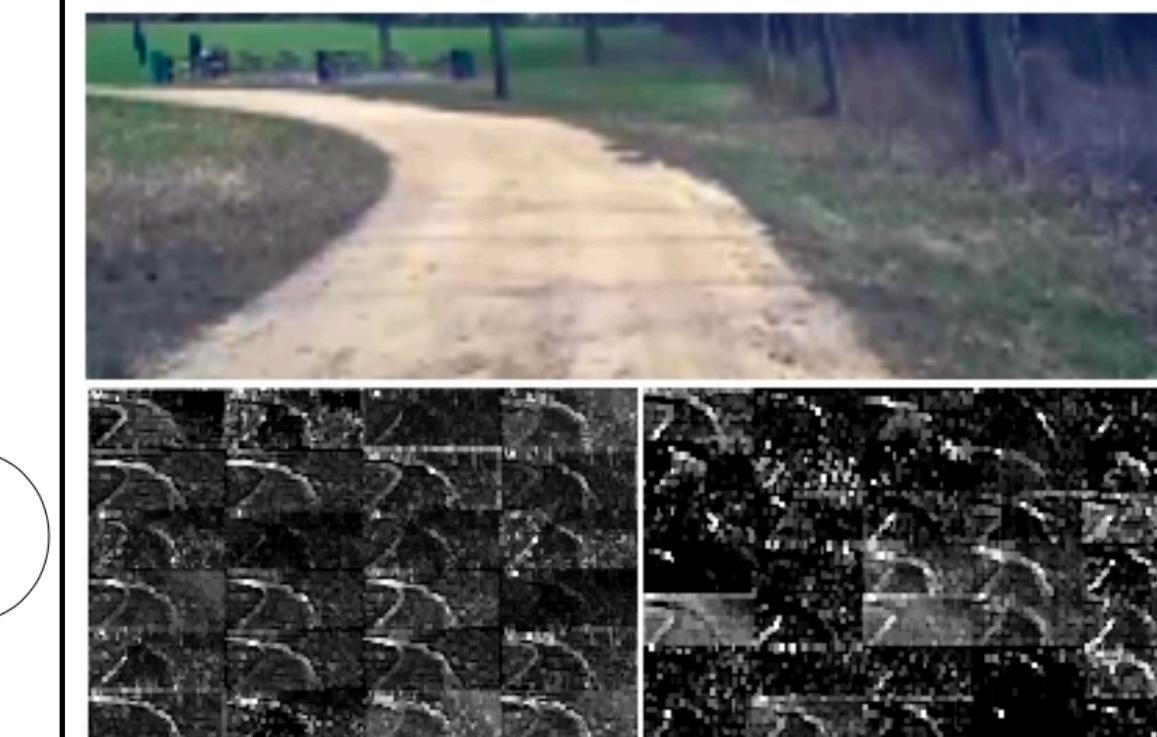


Block-diagram of the drive simulator.

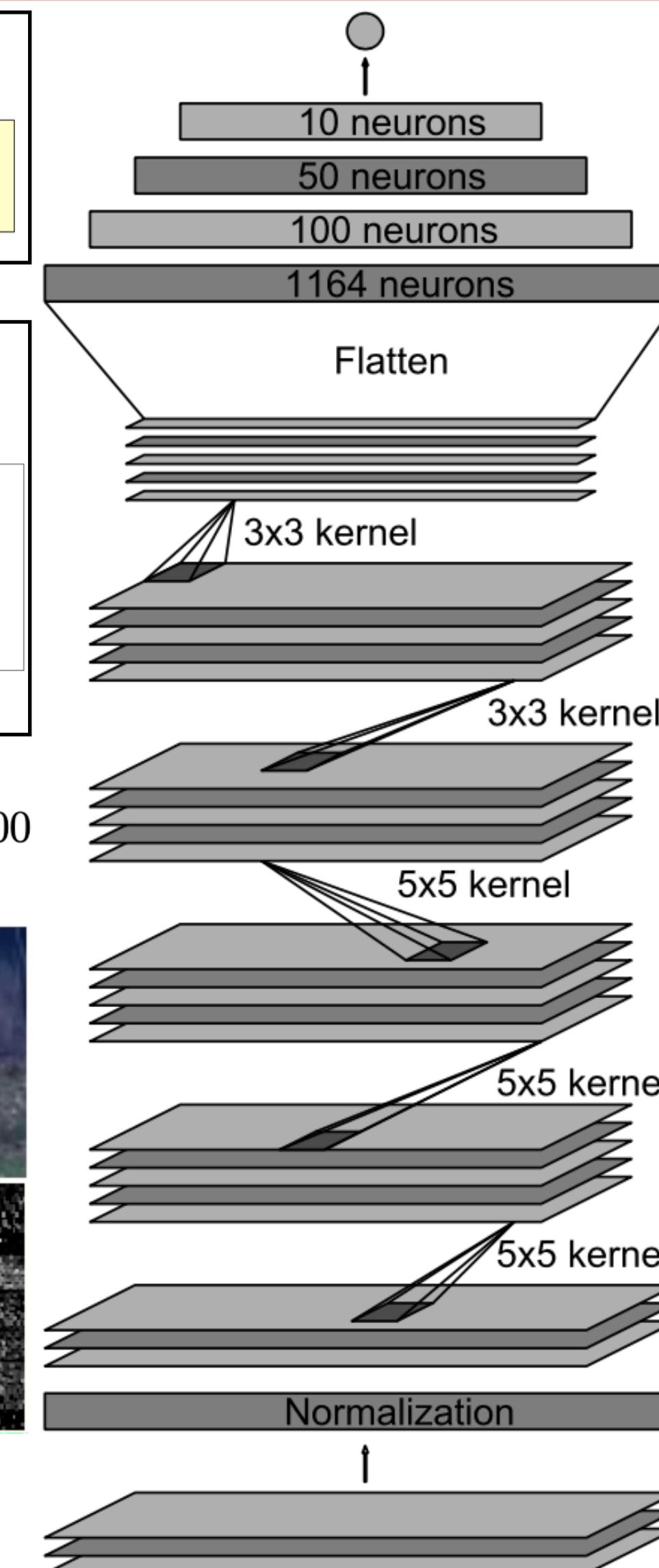


Evaluation Metric

$$\text{autonomy} = (1 - \frac{(\text{number of interventions}) \cdot 6 \text{ seconds}}{\text{elapsed time [seconds]}}) \cdot 100$$



Activations of the first & second layer feature maps.



Output: vehicle control

Fully-connected layer

Fully-connected layer

Fully-connected layer

Convolutional feature map
64@1x18

Convolutional feature map
64@3x20

Convolutional feature map
48@5x22

Convolutional feature map
36@14x47

Convolutional feature map
24@31x98

Normalized input planes
3@66x200

Input planes
3@66x200



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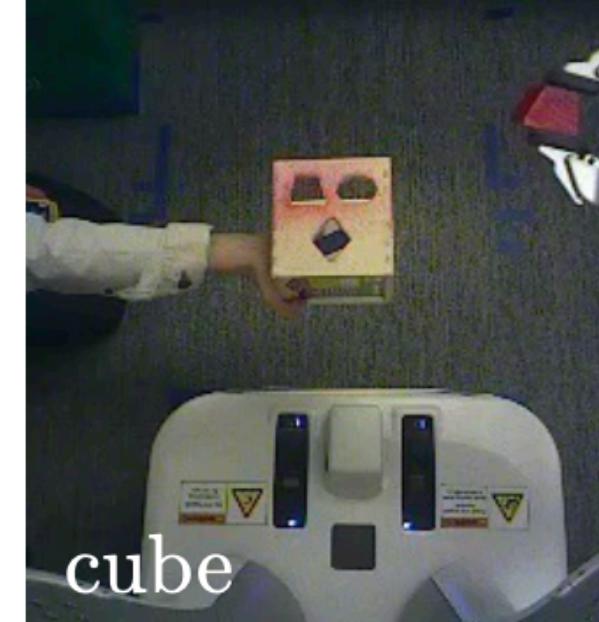
End-To-End Training Of Deep Visuomotor Policies



[YouTube Video](#)



hanger



cube



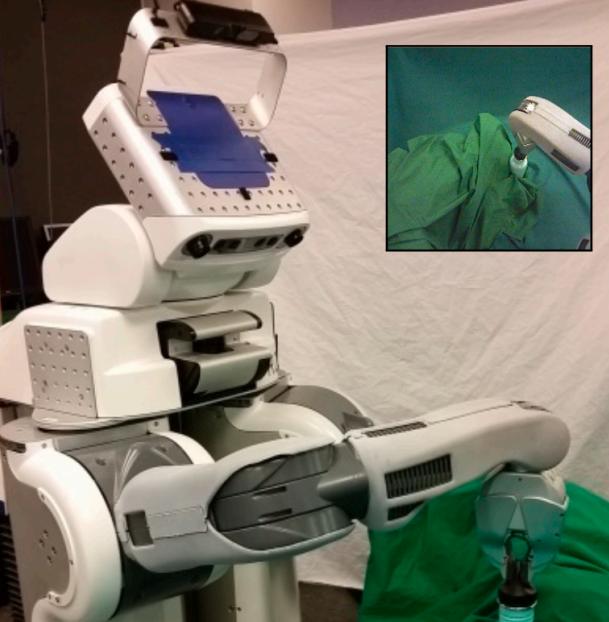
hammer



bottle



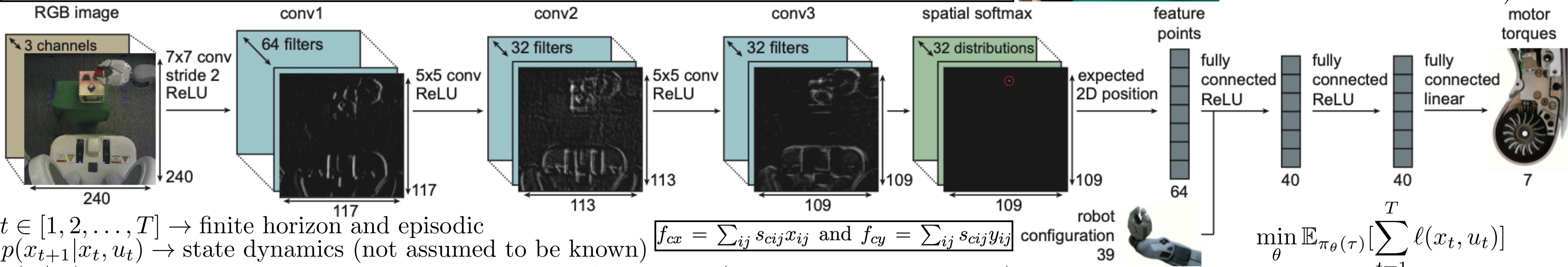
bottle



PR2

Inserting a block into a shape sorting cube, screwing a cap onto a bottle, fitting the claw of a toy hammer under a nail with various grasps, and placing a coat hanger on a rack with a PR2 robot

<http://sites.google.com/site/visuomotorpolicy>
 $\pi_\theta(u_t|o_t) \rightarrow \text{policy}$
 $u_t \rightarrow \text{actions}$
 (motor torque commands)
 $o_t \rightarrow \text{observations}$
 (an image from robot's onboard camera)
 $x_t \rightarrow \text{states}$
 (joint angles of the robot,
 positions of objects in the world,
 and their time derivatives)



$t \in [1, 2, \dots, T] \rightarrow$ finite horizon and episodic

$p(x_{t+1}|x_t, u_t) \rightarrow$ state dynamics (not assumed to be known)

$p(o_t|x_t) \rightarrow$ observations are a stochastic consequence of the states (not assumed to be known)

$\pi_\theta(u_t|x_t) = \int \pi_\theta(u_t|o_t)p(o_t|x_t)do_t \rightarrow$ distribution over actions under the policy conditioned on the state

$\tau = \{x_1, u_1, x_2, u_2, \dots, x_T, u_T\} \rightarrow$ trajectory

$$p(\mathbf{u}_t|\mathbf{x}_t) = \mathcal{N}(\mathbf{K}_t \mathbf{x}_t + \mathbf{k}_t, \mathbf{C}_t)$$

$\pi_\theta(\tau) = p(x_1) \prod_{t=1}^T \pi_\theta(u_t|x_t)p(x_{t+1}|x_t, u_t) \rightarrow$ distribution over trajectories

$$p(\mathbf{x}_{t+1}|\mathbf{x}_t, \mathbf{u}_t) = \mathcal{N}(f_{xt}\mathbf{x}_t + f_{ut}\mathbf{u}_t + f_{ct}, \mathbf{F}_t)$$

$\ell(x_t, u_t) \rightarrow$ cost function

Guided Policy Search

$$\min_{\theta, p} \mathbb{E}_{p(\tau)}[\ell(\tau)]$$

s.t. $p(u_t|x_t) = \pi_\theta(u_t|x_t)$

$p(\tau) \rightarrow$ guiding distribution

Alternating Direction Method of Multipliers

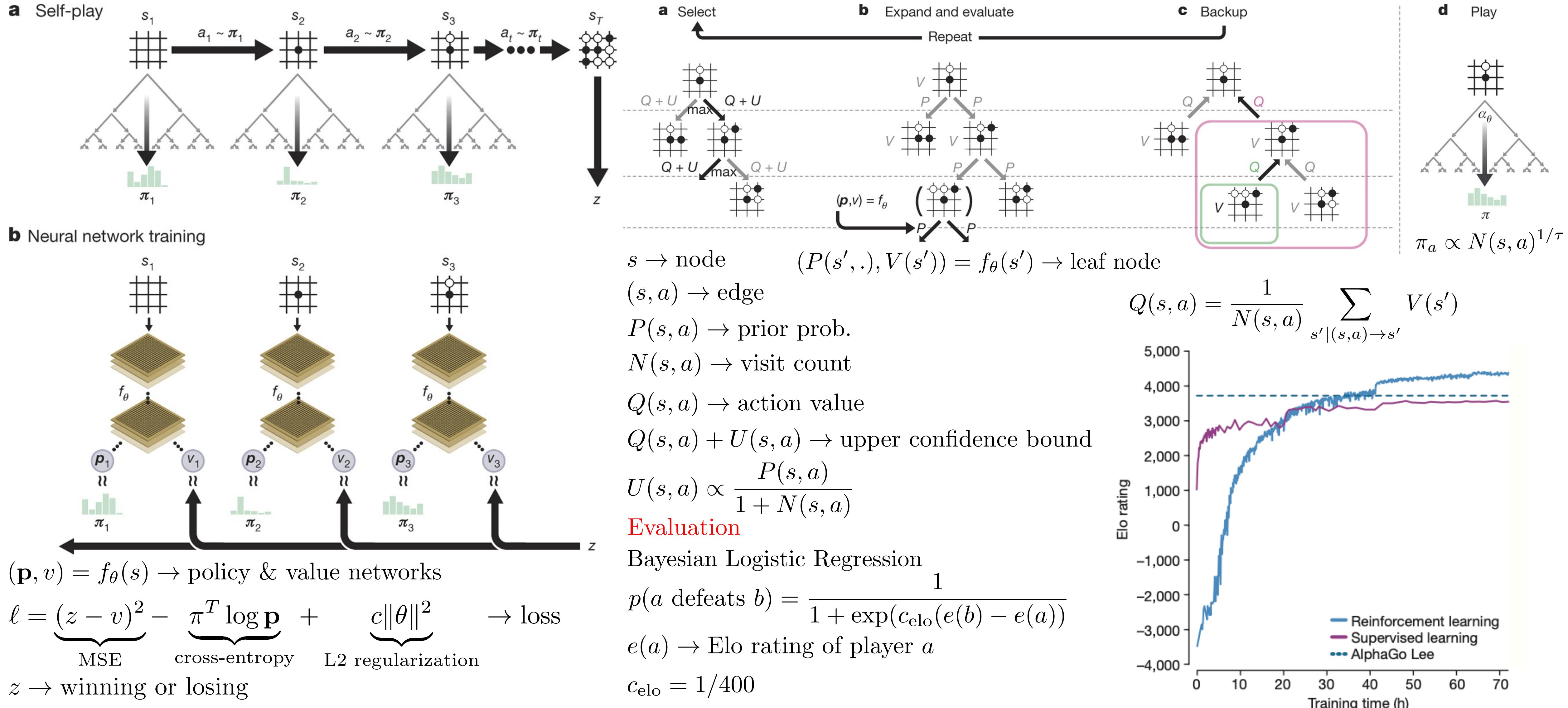


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[YouTube Video](#)

Mastering the game of Go without human knowledge



Silver, David, et al. "Mastering the game of go without human knowledge." *nature* 550.7676 (2017): 354-359.

A general reinforcement learning algorithm that masters chess, shogi, and Go through self-play


[YouTube Video](#)

$$(\mathbf{p}, v) = f_{\theta}(s)$$

$s \rightarrow$ board position

$\mathbf{p} \rightarrow$ move probability

$a \rightarrow$ action

$$p_a = Pr(a|s)$$

$v \rightarrow$ expected outcome z of the game from position s

$$v \approx \mathbb{E}[z|s]$$

$z = +1$ (win), 0 (draw), -1 (lose)

Monte-Carlo Tree Search (MCTS)

$s_{\text{root}} \rightarrow$ root state

$$\pi_a = Pr(a|s_{\text{root}})$$

$$\ell = (z - v)^2 - \pi^T \log \mathbf{p} + c \|\theta\|^2 \rightarrow \text{loss}$$

Search

$$\{ \underbrace{N(s, a)}_{\text{visit count}}, \underbrace{W(s, a)}_{\text{total action-value}}, \underbrace{Q(s, a)}_{\text{mean action-value}}, \underbrace{P(s, a)}_{\text{prior prob.}} \}$$

set of statistics stored at each state-action pair (s, a)

$s_0 \rightarrow$ root node of the tree search

$s_L \rightarrow$ leaf node at time-step L

$$a_t = \arg \max_a (Q(s_t, a) + U(s_t, a)), \text{ for } t < L$$

$$U(s, a) = C(s) P(s, a) \sqrt{N(s)} / (1 + N(s, a))$$

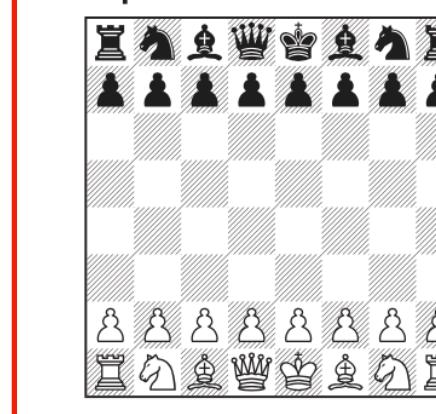
parent visit count

$$C(s) = \log ((1 + N(s) + c_{\text{base}}) / c_{\text{base}}) + c_{\text{init}}$$

exploration rate

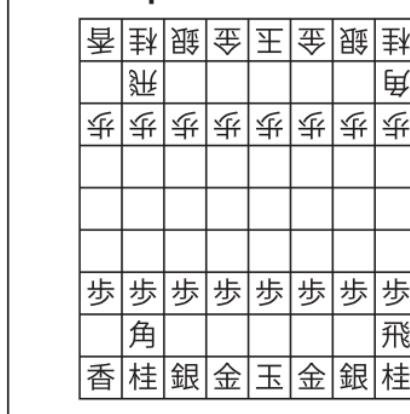
Chess

AlphaZero vs. Stockfish



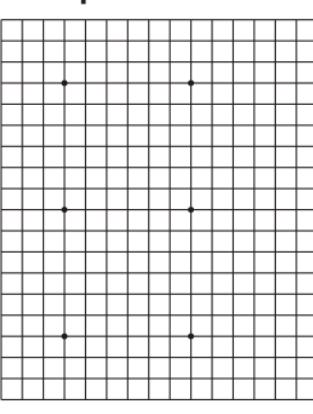
Shogi

AlphaZero vs. Elmo

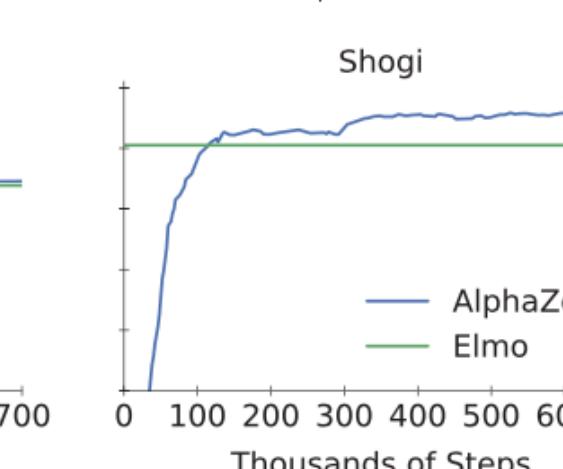


Go

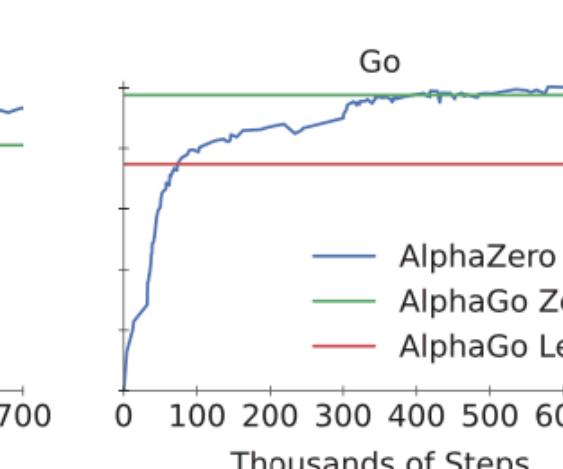
AlphaZero vs. AGO



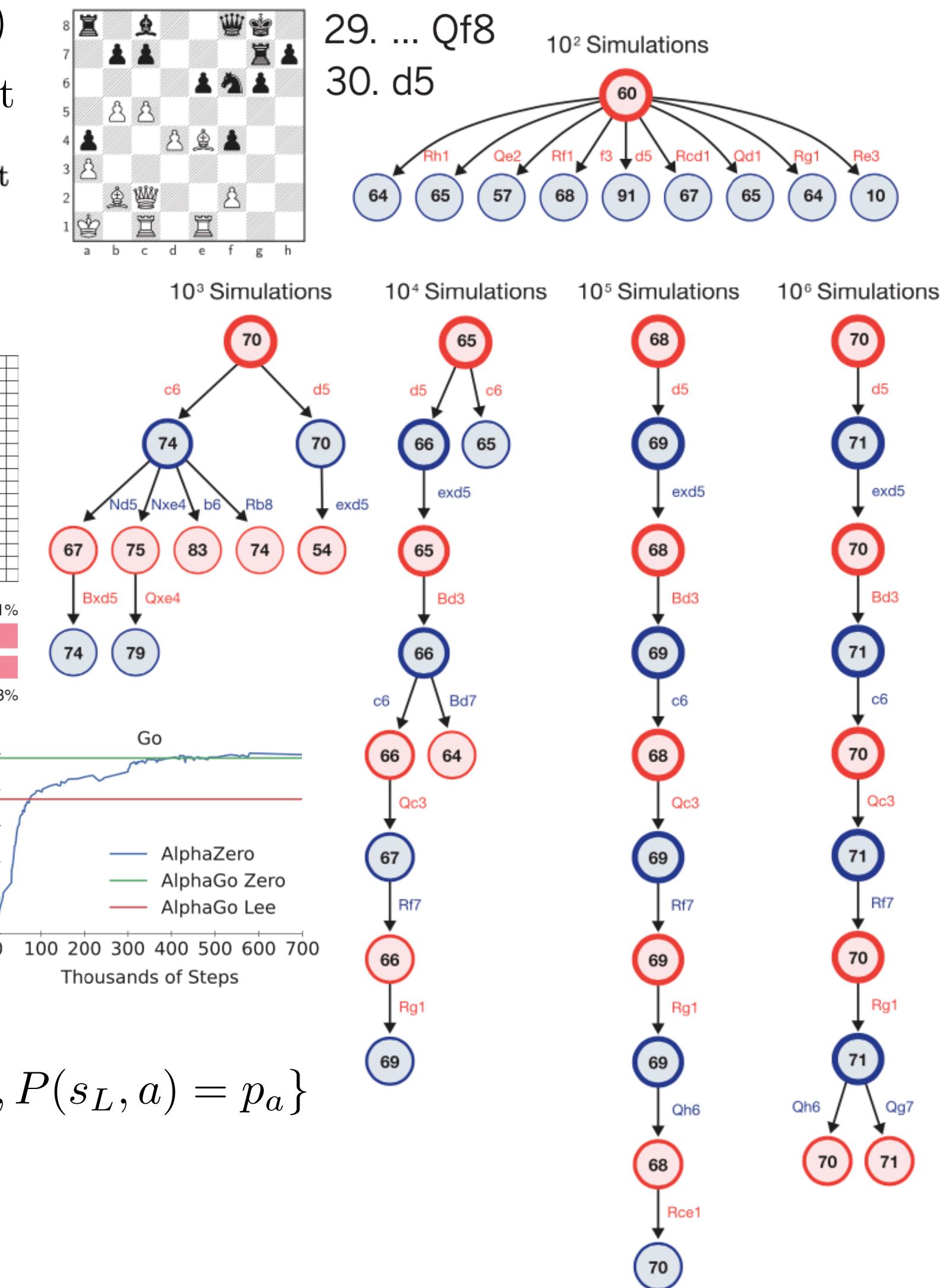
AlphaZero
Stockfish



AlphaZero
Elmo



AlphaZero
AGO Zero
AGO Lee





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Proximal Policy Optimization Algorithms



YouTube Video

Policy Gradient Methods

$$\hat{g} = \hat{\mathbb{E}}_t [\nabla_{\theta} \log \pi_{\theta}(a_t | s_t) \hat{A}_t] \rightarrow \text{policy gradient estimator}$$

policy
estimator of the advantage function at timestep t
empirical average over a finite batch of samples

$$L^{PG}(\theta) = \hat{\mathbb{E}}_t [\log \pi_{\theta}(a_t | s_t) \hat{A}_t]$$

Trust Region Methods

$$\max_{\theta} \hat{\mathbb{E}}_t \left[\frac{\pi_{\theta}(a_t | s_t)}{\pi_{\theta_{\text{old}}}(a_t | s_t)} \hat{A}_t \right] \rightarrow \text{linear approximation}$$

conjugate gradient algorithm

s.t. $\hat{\mathbb{E}}_t [\text{KL}(\pi_{\theta_{\text{old}}}(.|s_t) \| \pi_{\theta}(.|s_t))] \leq \delta \rightarrow \text{quadratic approximation}$

$$\max_{\theta} \hat{\mathbb{E}}_t \left[\frac{\pi_{\theta}(a_t | s_t)}{\pi_{\theta_{\text{old}}}(a_t | s_t)} \hat{A}_t - \beta \text{KL}(\pi_{\theta_{\text{old}}}(.|s_t) \| \pi_{\theta}(.|s_t)) \right]$$

Clipped Surrogate Objective

$$r_t(\theta) := \frac{\pi_{\theta}(a_t | s_t)}{\pi_{\theta_{\text{old}}}(a_t | s_t)} \implies r_t(\theta_{\text{old}}) = 1$$

prob. ratio

$$L^{CPI}(\theta) = \hat{\mathbb{E}}_t \left[\frac{\pi_{\theta}(a_t | s_t)}{\pi_{\theta_{\text{old}}}(a_t | s_t)} \hat{A}_t \right] = \hat{\mathbb{E}}_t [r_t(\theta) \hat{A}_t]$$

CPI: Conservative Policy Iteration

$$L^{CLIP}(\theta) = \hat{\mathbb{E}}_t \left[\min \underbrace{(r_t(\theta) \hat{A}_t)}_{L^{CPI}}, \underbrace{\text{clip}(r_t(\theta), 1 - \epsilon, 1 + \epsilon) \hat{A}_t}_{\text{removes the incentive for moving } r_t \text{ outside of the interval } [1 - \epsilon, 1 + \epsilon]} \right]$$

pessimistic lower bound

$$L_t^{CLIP+VF+S}(\theta) = \hat{\mathbb{E}}_t [L_t^{CLIP}(\theta) - c_1 L_t^{VF}(\theta) + c_2 S[\pi_{\theta}](s_t)]$$

$(V_{\theta}(s_t) - V_t^{\text{targ}})^2$ entropy bonus

$$\hat{A}_t = -V(s_t) + r_t + \gamma r_{t+1} + \dots + \gamma^{T-t+1} r_{T-1} + \gamma^{T-t} V(s_T)$$

$$\hat{A}_t = \delta_t + (\gamma \lambda) \delta_{t+1} + \dots + (\gamma \lambda)^{T-t+1} \delta_{T-1},$$

where $\delta_t = r_t + \gamma V(s_{t+1}) - V(s_t)$ same as above if $\lambda = 1$

Algorithm 1 PPO, Actor-Critic Style

```

for iteration=1,2,... do
    for actor=1,2,...,N do
        Run policy  $\pi_{\theta_{\text{old}}}$  in environment for  $T$  timesteps
        Compute advantage estimates  $\hat{A}_1, \dots, \hat{A}_T$ 
    end for
    Optimize surrogate  $L$  wrt  $\theta$ , with  $K$  epochs and minibatch size  $M \leq NT$ 
     $\theta_{\text{old}} \leftarrow \theta$ 
end for

```



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Model-Agnostic Meta-Learning for Fast Adaptation of Deep Networks



[YouTube Playlist](#)

Goal: Train a model on a variety of learning tasks such that it can solve new learning tasks using only a small number of training examples

Tasks as training examples!

$f \rightarrow$ model

$x \mapsto a$ outputs
observations

$\mathcal{T} = \{ \mathcal{L}(x_1, a_1, \dots, x_H, a_H), q(x_1), q(x_{t+1}|x_t, a_t), H \}$

episode length
transition distribution
distribution over initial observations

$H = 1$ in *i.i.d* supervised problems

$p(\mathcal{T}) \rightarrow$ distribution over tasks

$$\min_{\theta} \sum_{\mathcal{T}_i \sim p(\mathcal{T})} \mathcal{L}_{\mathcal{T}_i}(f_{\theta'_i}) = \sum_{\mathcal{T}_i \sim p(\mathcal{T})} \mathcal{L}_{\mathcal{T}_i}(f_{\theta - \alpha \nabla_{\theta} \mathcal{L}_{\mathcal{T}_i}(f_{\theta})})$$

Optimize the model parameters such that one or a small number of gradient steps on a new task will produce maximally effective behavior on that task

$$\mathcal{L}_{\mathcal{T}_i}(f_{\phi}) = \sum_{\mathbf{x}^{(j)}, \mathbf{y}^{(j)} \sim \mathcal{T}_i} \|f_{\phi}(\mathbf{x}^{(j)}) - \mathbf{y}^{(j)}\|_2^2, \rightarrow \text{Regression}$$

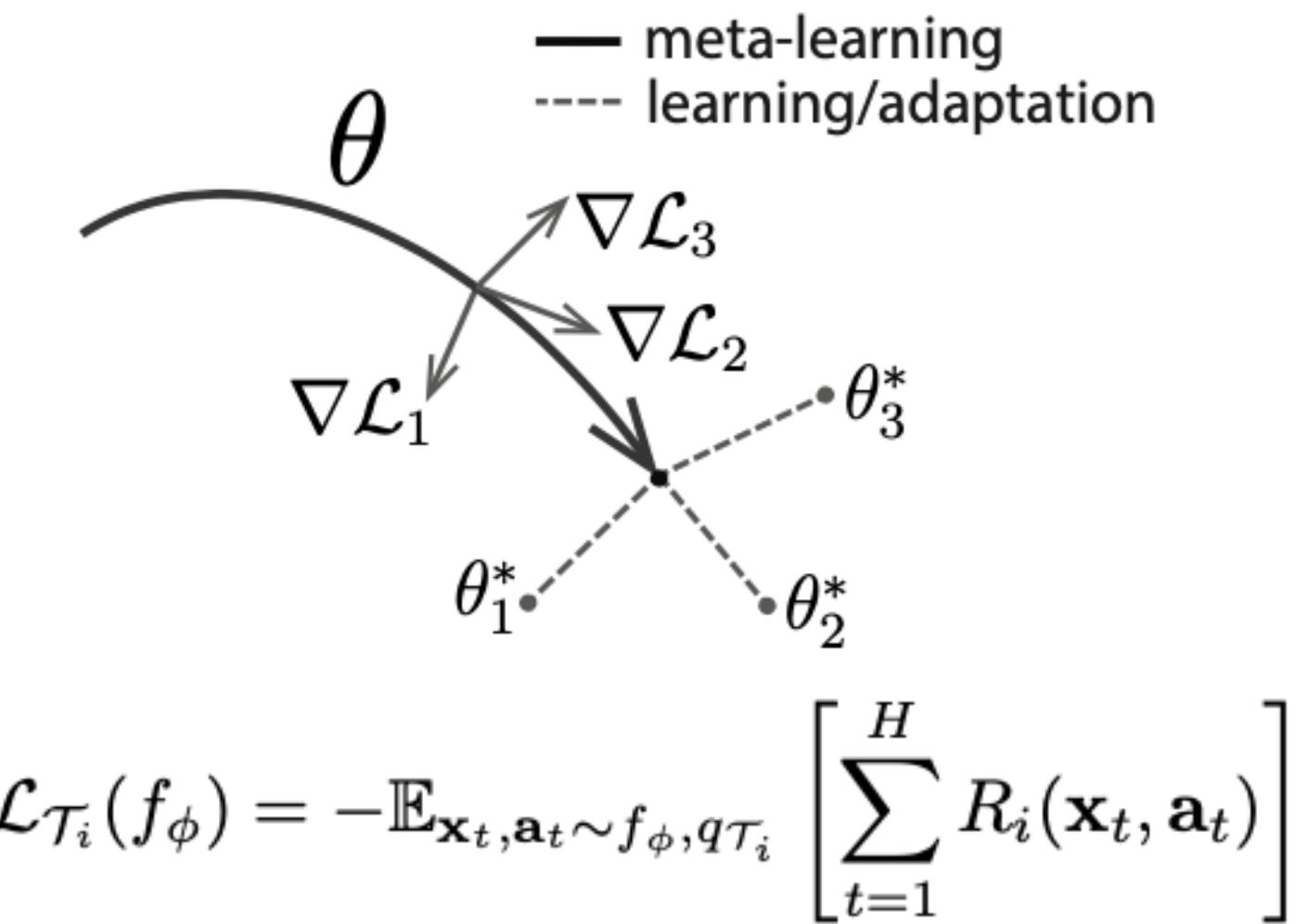
$$\begin{aligned} \mathcal{L}_{\mathcal{T}_i}(f_{\phi}) &= \sum_{\mathbf{x}^{(j)}, \mathbf{y}^{(j)} \sim \mathcal{T}_i} \mathbf{y}^{(j)} \log f_{\phi}(\mathbf{x}^{(j)}) \\ &\quad + (1 - \mathbf{y}^{(j)}) \log(1 - f_{\phi}(\mathbf{x}^{(j)})) \end{aligned} \rightarrow \text{Classification}$$

Algorithm 1 Model-Agnostic Meta-Learning

Require: $p(\mathcal{T})$: distribution over tasks

Require: α, β : step size hyperparameters

- 1: randomly initialize θ
 - 2: **while** not done **do**
 - 3: Sample batch of tasks $\mathcal{T}_i \sim p(\mathcal{T})$
 - 4: **for all** \mathcal{T}_i **do**
 - 5: Evaluate $\nabla_{\theta} \mathcal{L}_{\mathcal{T}_i}(f_{\theta})$ with respect to K examples
 - 6: Compute adapted parameters with gradient descent: $\theta'_i = \theta - \alpha \nabla_{\theta} \mathcal{L}_{\mathcal{T}_i}(f_{\theta})$
 - 7: **end for**
 - 8: Update $\theta \leftarrow \theta - \beta \nabla_{\theta} \sum_{\mathcal{T}_i \sim p(\mathcal{T})} \mathcal{L}_{\mathcal{T}_i}(f_{\theta'_i})$
 - 9: **end while**
-



Algorithm 2 MAML for Few-Shot Supervised Learning

Require: $p(\mathcal{T})$: distribution over tasks

Require: α, β : step size hyperparameters

- 1: randomly initialize θ
 - 2: **while** not done **do**
 - 3: Sample batch of tasks $\mathcal{T}_i \sim p(\mathcal{T})$
 - 4: **for all** \mathcal{T}_i **do**
 - 5: Sample K datapoints $\mathcal{D} = \{\mathbf{x}^{(j)}, \mathbf{y}^{(j)}\}$ from \mathcal{T}_i
 - 6: Evaluate $\nabla_{\theta} \mathcal{L}_{\mathcal{T}_i}(f_{\theta})$ using \mathcal{D} and $\mathcal{L}_{\mathcal{T}_i}$ in Equation (2) or (3)
 - 7: Compute adapted parameters with gradient descent: $\theta'_i = \theta - \alpha \nabla_{\theta} \mathcal{L}_{\mathcal{T}_i}(f_{\theta})$
 - 8: Sample datapoints $\mathcal{D}'_i = \{\mathbf{x}^{(j)}, \mathbf{y}^{(j)}\}$ from \mathcal{T}_i for the meta-update
 - 9: **end for**
 - 10: Update $\theta \leftarrow \theta - \beta \nabla_{\theta} \sum_{\mathcal{T}_i \sim p(\mathcal{T})} \mathcal{L}_{\mathcal{T}_i}(f_{\theta'_i})$ using each \mathcal{D}'_i and $\mathcal{L}_{\mathcal{T}_i}$ in Equation 2 or 3
 - 11: **end while**
-

Algorithm 3 MAML for Reinforcement Learning

Require: $p(\mathcal{T})$: distribution over tasks

Require: α, β : step size hyperparameters

- 1: randomly initialize θ
 - 2: **while** not done **do**
 - 3: Sample batch of tasks $\mathcal{T}_i \sim p(\mathcal{T})$
 - 4: **for all** \mathcal{T}_i **do**
 - 5: Sample K trajectories $\mathcal{D} = \{(\mathbf{x}_1, \mathbf{a}_1, \dots, \mathbf{x}_H)\}$ using f_{θ} in \mathcal{T}_i
 - 6: Evaluate $\nabla_{\theta} \mathcal{L}_{\mathcal{T}_i}(f_{\theta})$ using \mathcal{D} and $\mathcal{L}_{\mathcal{T}_i}$ in Equation 4
 - 7: Compute adapted parameters with gradient descent: $\theta'_i = \theta - \alpha \nabla_{\theta} \mathcal{L}_{\mathcal{T}_i}(f_{\theta})$
 - 8: Sample trajectories $\mathcal{D}'_i = \{(\mathbf{x}_1, \mathbf{a}_1, \dots, \mathbf{x}_H)\}$ using $f_{\theta'_i}$ in \mathcal{T}_i
 - 9: **end for**
 - 10: Update $\theta \leftarrow \theta - \beta \nabla_{\theta} \sum_{\mathcal{T}_i \sim p(\mathcal{T})} \mathcal{L}_{\mathcal{T}_i}(f_{\theta'_i})$ using each \mathcal{D}'_i and $\mathcal{L}_{\mathcal{T}_i}$ in Equation 4
 - 11: **end while**
-



Learning hand-eye coordination for robotic grasping with deep learning and large-scale data collection



[YouTube Video](https://youtu.be/cXaic_k80uM)

https://youtu.be/cXaic_k80uM

Visual servoing: vision-based robot control

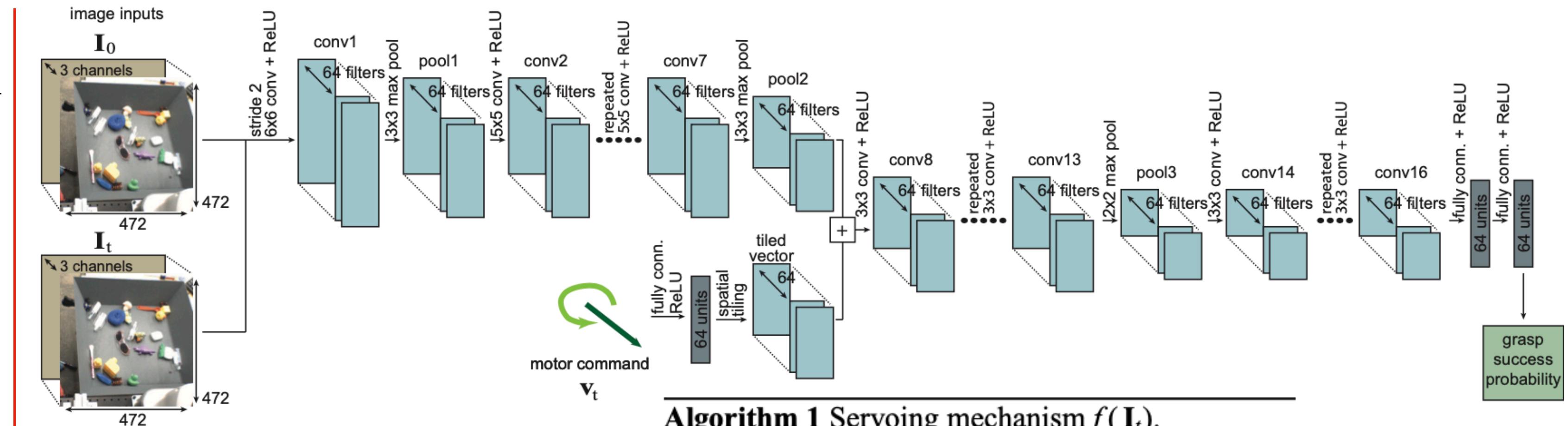
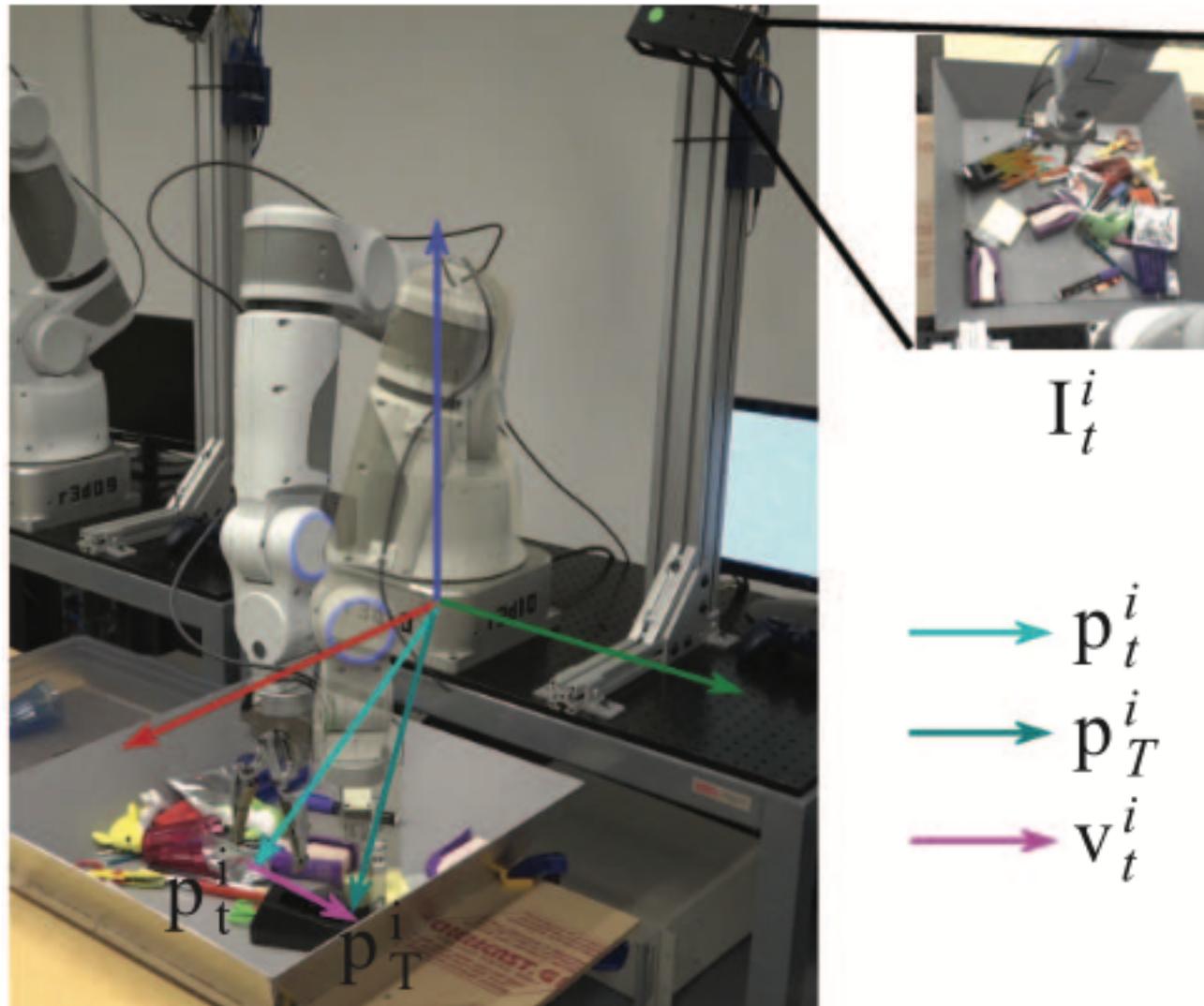
$g \rightarrow$ grasp success prediction network

$I_t \rightarrow$ visual input

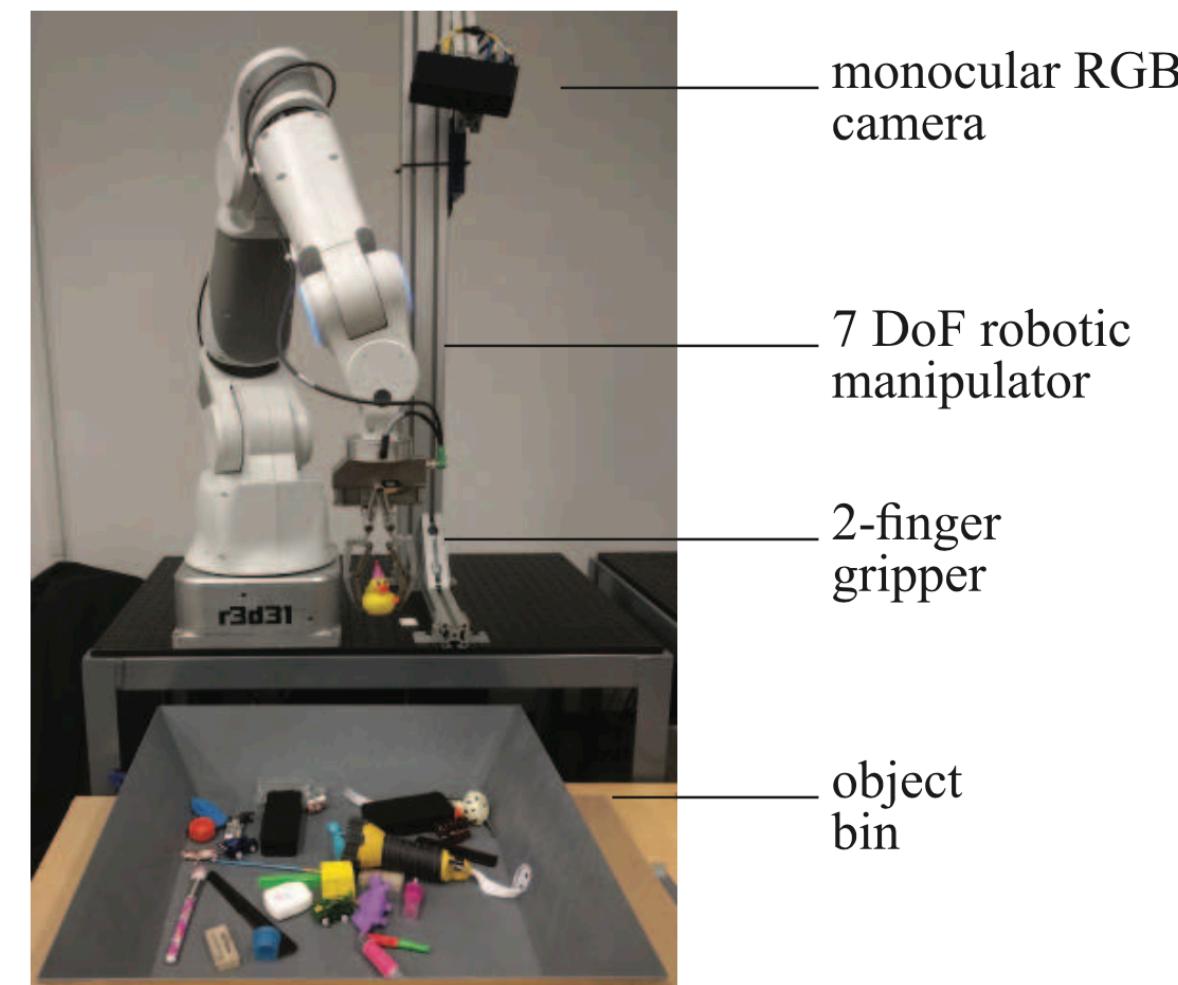
$v_t \rightarrow$ task-space motion command

$g(I_t, v_t) \rightarrow$ predicted probability that executing the command v_t will produce a successful grasp

$f(I_t) \rightarrow$ servoing mechanism

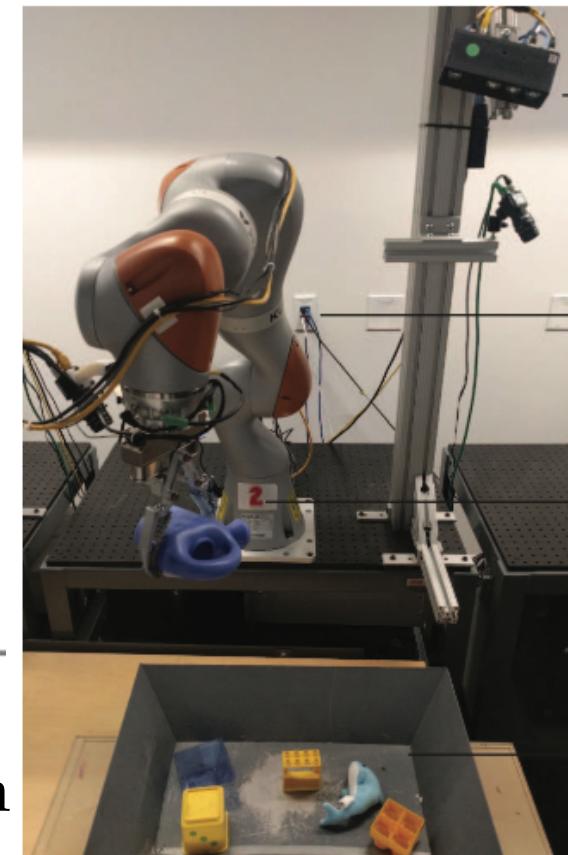


$$(I_t^i, \underbrace{P_T^i - p_t^i}_{v_t^i}, \ell_i) \rightarrow T \text{ training samples} \quad \underbrace{\ell_i}_{\text{label}}$$



Algorithm 1 Servoing mechanism $f(\mathbf{I}_t)$.

- 1: Given current image \mathbf{I}_t and network g .
- 2: Infer \mathbf{v}_t^* using g and CEM.
- 3: Evaluate $p = g(\mathbf{I}_t, \emptyset) / g(\mathbf{I}_t, \mathbf{v}_t^*)$.
- 4: **if** $p > 0.9$ **then** No Motion
- 5: Output \emptyset , close gripper.
- 6: **else if** $p \leq 0.5$ **then**
- 7: Modify \mathbf{v}_t^* to raise gripper height and execute \mathbf{v}_t^* .
- 8: **else**
- 9: Execute \mathbf{v}_t^* .
- 10: **end if**



Cross-Entropy Method (CEM)

A simple derivative-free optimization algorithm

- 1) Sample $N=64$ values from $\mathcal{N}(0, I)$
- 2) Choose the best $M = 6$ and fit a Gaussian to these M samples
- 3) Sample $N=64$ value from this Gaussian
- 4) Repeat steps 2 & 3 three times
- 5) Return the best v_t^*

Soft Actor-Critic: Off-Policy Maximum Entropy Deep Reinforcement Learning with a Stochastic Actor


[YouTube Video](#)

Model-free Deep Reinforcement Learning

- very high sample complexity
- brittle convergence properties (meticulous hyper-parameter tuning)

Continuous state and action spaces

$(\mathcal{S}, \mathcal{A}, p, r) \rightarrow$ infinite-horizon Markov decision process (MDP)

$\mathcal{S} \rightarrow$ state space (continuous)

$\mathcal{A} \rightarrow$ action space (continuous)

$p : \mathcal{S} \times \mathcal{S} \times \mathcal{A} \rightarrow [0, \infty)$

unknown state transition probability

probability density of the next state $s_{t+1} \in \mathcal{S}$

given the current state $s_t \in \mathcal{S}$ and action $a_t \in \mathcal{A}$

$r : \mathcal{S} \times \mathcal{A} \rightarrow [r_{\min}, r_{\max}]$

reward emitted on each transition

$\rho_\pi(s_t) \rightarrow$ state marginal of the trajectory distribution induced by a policy $\pi(a_t|s_t)$

$\rho_\pi(s_t, a_t) \rightarrow$ state-action marginal

Maximum Entropy Reinforcement Learning

$$J(\pi) = \sum_{t=0}^T \mathbb{E}_{(\mathbf{s}_t, \mathbf{a}_t) \sim \rho_\pi} [r(\mathbf{s}_t, \mathbf{a}_t) + \alpha \mathcal{H}(\pi(\cdot | \mathbf{s}_t))]$$

$Q : \mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$

soft Q -value

$\mathcal{T}^\pi \rightarrow$ Bellman backup operator

$$\mathcal{T}^\pi Q(\mathbf{s}_t, \mathbf{a}_t) \triangleq r(\mathbf{s}_t, \mathbf{a}_t) + \gamma \mathbb{E}_{\mathbf{s}_{t+1} \sim p} [V(\mathbf{s}_{t+1})]$$

$$V(\mathbf{s}_t) = \mathbb{E}_{\mathbf{a}_t \sim \pi} [Q(\mathbf{s}_t, \mathbf{a}_t) - \log \pi(\mathbf{a}_t | \mathbf{s}_t)]$$

soft state value function

Lemma (Soft Policy Evaluation)

$$Q^{k+1} = \mathcal{T}^\pi Q^k \implies Q^k \rightarrow \text{soft } Q\text{-value as } k \rightarrow \infty$$

Lemma (Soft Policy Improvement)

$$\begin{aligned} \pi_{\text{new}} &= \arg \min_{\pi' \in \Pi} D_{\text{KL}} \left(\pi'(\cdot | \mathbf{s}_t) \parallel \frac{\exp(Q^{\pi_{\text{old}}}(\mathbf{s}_t, \cdot))}{Z^{\pi_{\text{old}}}(\mathbf{s}_t)} \right) \\ &\implies Q^{\pi_{\text{new}}}(\mathbf{s}_t, \mathbf{a}_t) \geq Q^{\pi_{\text{old}}}(\mathbf{s}_t, \mathbf{a}_t), \forall (\mathbf{s}_t, \mathbf{a}_t) \in \mathcal{S} \times \mathcal{A} \end{aligned}$$

Theorem (Soft Policy Iteration)

Repeated application of soft policy evaluation and soft policy improvement converges to a policy π^* such that $Q^{\pi^*}(\mathbf{s}_t, \mathbf{a}_t) \geq Q^\pi(\mathbf{s}_t, \mathbf{a}_t), \forall \pi \in \Pi$.

Soft Actor-Critic

$V_\psi(\mathbf{s}_t) \rightarrow$ parametrized state value function

$Q_\theta(\mathbf{s}_t, \mathbf{a}_t) \rightarrow$ parametrized soft Q -function

$\pi_\phi(\mathbf{a}_t | \mathbf{s}_t) \rightarrow$ tractable policy

$$J_V(\psi) = \mathbb{E}_{\mathbf{s}_t \sim \mathcal{D}} \left[\frac{1}{2} (V_\psi(\mathbf{s}_t) - \mathbb{E}_{\mathbf{a}_t \sim \pi_\phi} [Q_\theta(\mathbf{s}_t, \mathbf{a}_t) - \log \pi_\phi(\mathbf{a}_t | \mathbf{s}_t)])^2 \right]$$

$$J_Q(\theta) = \mathbb{E}_{(\mathbf{s}_t, \mathbf{a}_t) \sim \mathcal{D}} \left[\frac{1}{2} (Q_\theta(\mathbf{s}_t, \mathbf{a}_t) - \hat{Q}(\mathbf{s}_t, \mathbf{a}_t))^2 \right]$$

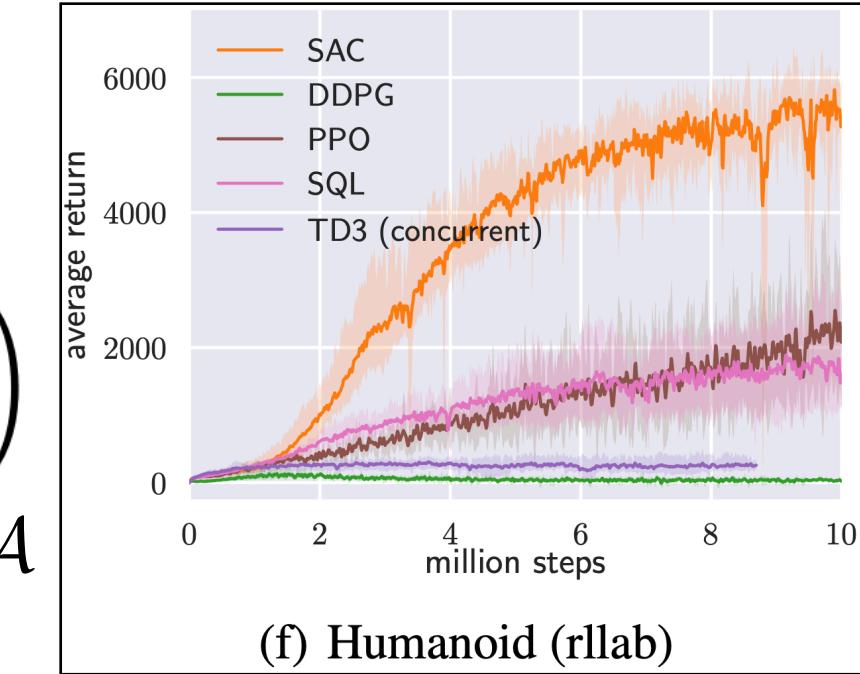
$$\hat{Q}(\mathbf{s}_t, \mathbf{a}_t) = r(\mathbf{s}_t, \mathbf{a}_t) + \gamma \mathbb{E}_{\mathbf{s}_{t+1} \sim p} [V_{\bar{\psi}}(\mathbf{s}_{t+1})]$$

$\bar{\psi}$ can be an exponentially moving average of the value network weights

$$J_\pi(\phi) = \mathbb{E}_{\mathbf{s}_t \sim \mathcal{D}} \left[D_{\text{KL}} \left(\pi_\phi(\cdot | \mathbf{s}_t) \parallel \frac{\exp(Q_\theta(\mathbf{s}_t, \cdot))}{Z_\theta(\mathbf{s}_t)} \right) \right]$$

$\mathbf{a}_t = f_\phi(\epsilon_t; \mathbf{s}_t) \rightarrow$ reparameterization trick

$$J_\pi(\phi) = \mathbb{E}_{\mathbf{s}_t \sim \mathcal{D}, \epsilon_t \sim \mathcal{N}} [\log \pi_\phi(f_\phi(\epsilon_t; \mathbf{s}_t) | \mathbf{s}_t) - Q_\theta(\mathbf{s}_t, f_\phi(\epsilon_t; \mathbf{s}_t))]$$



Algorithm 1 Soft Actor-Critic

Initialize parameter vectors $\psi, \bar{\psi}, \theta, \phi$.

for each iteration do

for each environment step do

$\mathbf{a}_t \sim \pi_\phi(\mathbf{a}_t | \mathbf{s}_t)$

$\mathbf{s}_{t+1} \sim p(\mathbf{s}_{t+1} | \mathbf{s}_t, \mathbf{a}_t)$

$\mathcal{D} \leftarrow \mathcal{D} \cup \{(\mathbf{s}_t, \mathbf{a}_t, r(\mathbf{s}_t, \mathbf{a}_t), \mathbf{s}_{t+1})\}$

end for

for each gradient step do

$\psi \leftarrow \psi - \lambda_V \hat{\nabla}_\psi J_V(\psi)$

$\theta_i \leftarrow \theta_i - \lambda_Q \hat{\nabla}_{\theta_i} J_Q(\theta_i)$ for $i \in \{1, 2\}$

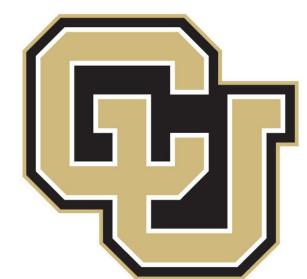
$\phi \leftarrow \phi - \lambda_\pi \hat{\nabla}_\phi J_\pi(\phi)$

$\bar{\psi} \leftarrow \tau \psi + (1 - \tau) \bar{\psi}$

end for

end for

defined implicitly in terms of f_ϕ
can be differentiated through!



Boulder



Questions?

[YouTube Playlist](#)
