Deep Reinforcement Learning

ECE448

Mark Hasegawa-Johnson, 5/2023

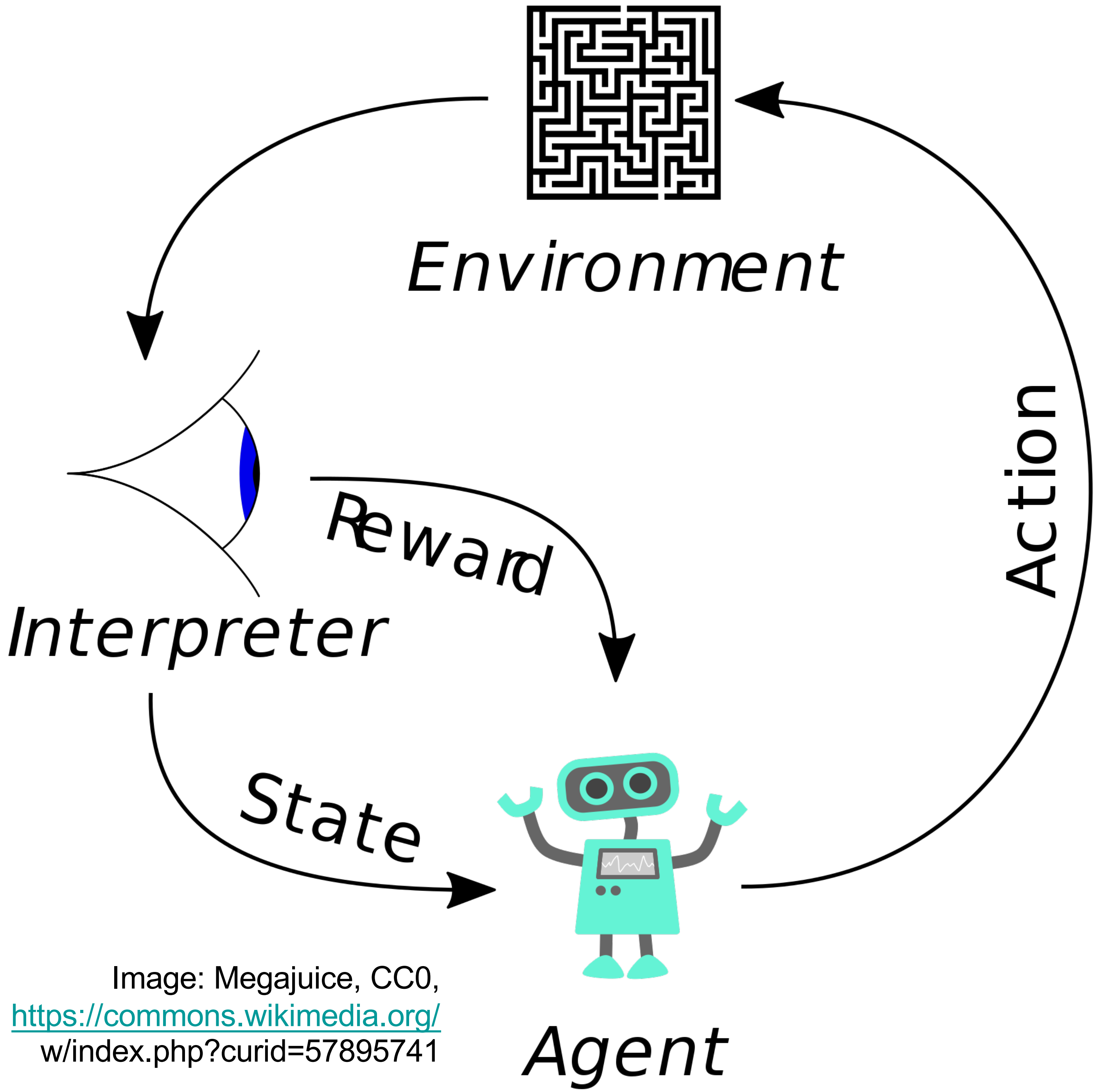


Image: Megajuice, CC0, https://commons.wikimedia.org/w/index.php?curid=57895741

Review: Reinforcement Learning

- Markov Decision Process (MDP): Given P(s'|s,a) and R(s), you can solve for $\pi^*(s)$, the optimal policy, by finding U(s), the value of each state, using either value iteration or policy iteration.
- Model-Based Reinforcement Learning: If P(s'|s,a) and R(s) are unknown, you can find for $\pi(s)$ by using the observation-model-policy loop.
- Model-Free Reinforcement Learning: Instead of learning P(s'|s,a) and then calculating $\pi(s)$, we can directly find the optimum action by learning Q(s,a).

Outline

- Imitation learning: learn the optimal policy by imitating a human
- Deep Q learning: compute Q(s,a) using a neural network
- Actor-Critic learning: The critic is deep-Q, while the actor just learns how to act

Policy Learning

Why can't we just learn a neural net (or even a table lookup) that does this:

$$s \longrightarrow \boxed{\text{Neural Net}} \longrightarrow a = \pi(s)$$

Probabilistic Policy

If we have $|A|$ possible, actions, $1 \leq a \leq |A|$, we could train the network to learn a hidden layer $h(s)$ so that:

$$\pi_a(s) = \frac{\exp(w_a^T h(s))}{\sum_{k=1}^{|A|} \exp(w_k^T h(s))} = P(A = a|S = s)$$

Meaning “the probability that the best action is a.”

How do we train it?

- Training data only give us (s_i, a_i, s_i', R_i).
- BAD IDEA: train the network to choose $\mathrm{A} = a_i$ that maximizes the immediate reward, R_i, and just ignore future rewards.
- GOOD IDEA: Train the network to maximize $U(s_i') =$ sum of all future rewards.
- PROBLEM: we don't know $U\left(s_i'\right)$.

$$\begin{gathered}(s_1, a_1, s_1', R_1)\\(s_2, a_2, s_2', R_2)\\(s_3, a_3, s_3', R_3)\\(s_4, a_4, s_4', R_4)\\(s_5, a_5, s_5', R_5)\\\vdots\end{gathered}$$

How to make Policy Learning trainable

1. Actor-Critic RL. We'll come back to this next time.
2. Imitation learning.

Imitation learning

- In some applications, you cannot bootstrap yourself from random policies
  - High-dimensional state and action spaces where most random trajectories fail miserably
  - Expensive to evaluate policies in the physical world, especially in cases of failure
- **Solution:** learn to imitate sample trajectories or demonstrations
  - This is also helpful when there is no natural reward formulation

Imitation learning: Discrete actions

- $\vec{s}_t$ = a representation of the state of the environment at time t (can be a real-valued vector)
- a_t= the action that a human actor performed in response to this state (discrete)
- $f_k(\vec{s}_t)$ = k^{th} element in the softmax output of a neural network, given $\vec{s}_t$ as the input
- Training criterion: train the neural network in order to minimize

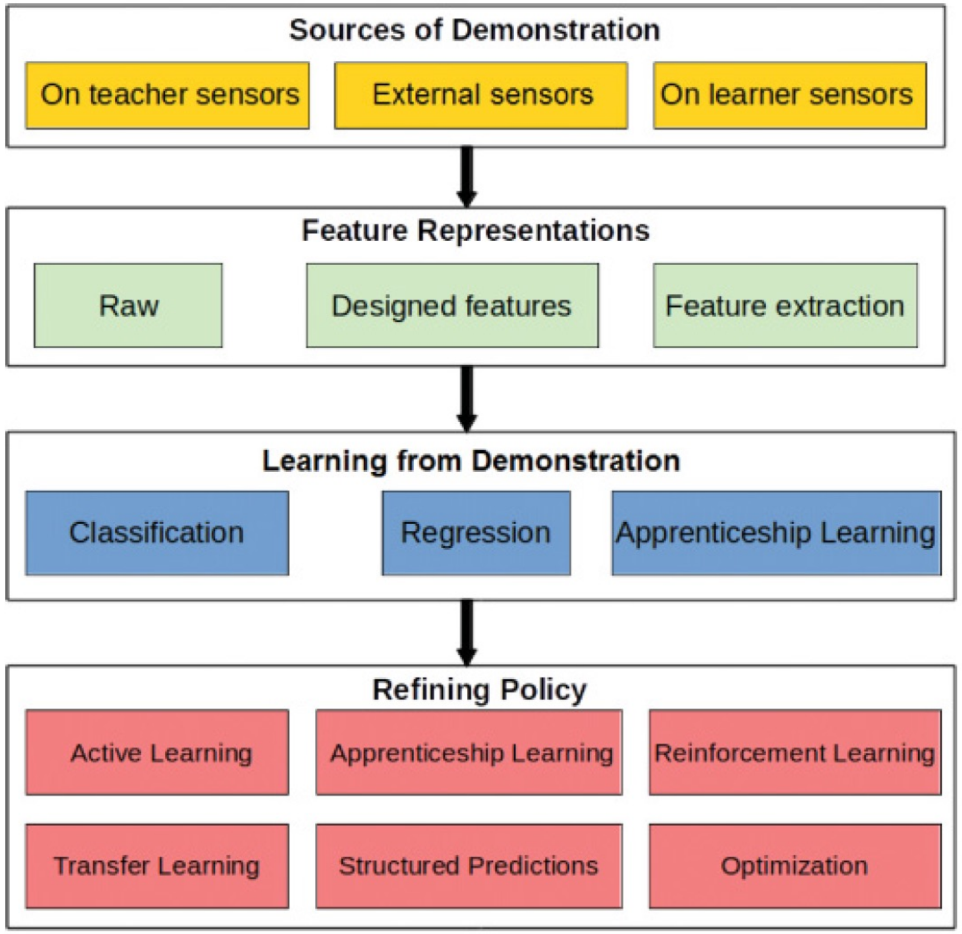
$$\mathcal{L} = -\log f_{a_t}(\vec{s}_t)$$

Imitation learning: Continuous actions

- $\vec{s}_t$ = a representation of the state of the environment at time t (can be a real-valued vector)
- a_t= the action that a human actor performed in response to this state (continuous)
- $f(\vec{s}_t)$ = real-valued output of a neural network, given $\vec{s}_t$ as the input
- Training criterion: train the neural network in order to minimize

$$\mathcal{L} = \frac{1}{2} E[(f(\vec{s}_t) - a_t)^2]$$

Overview of imitation learning methods

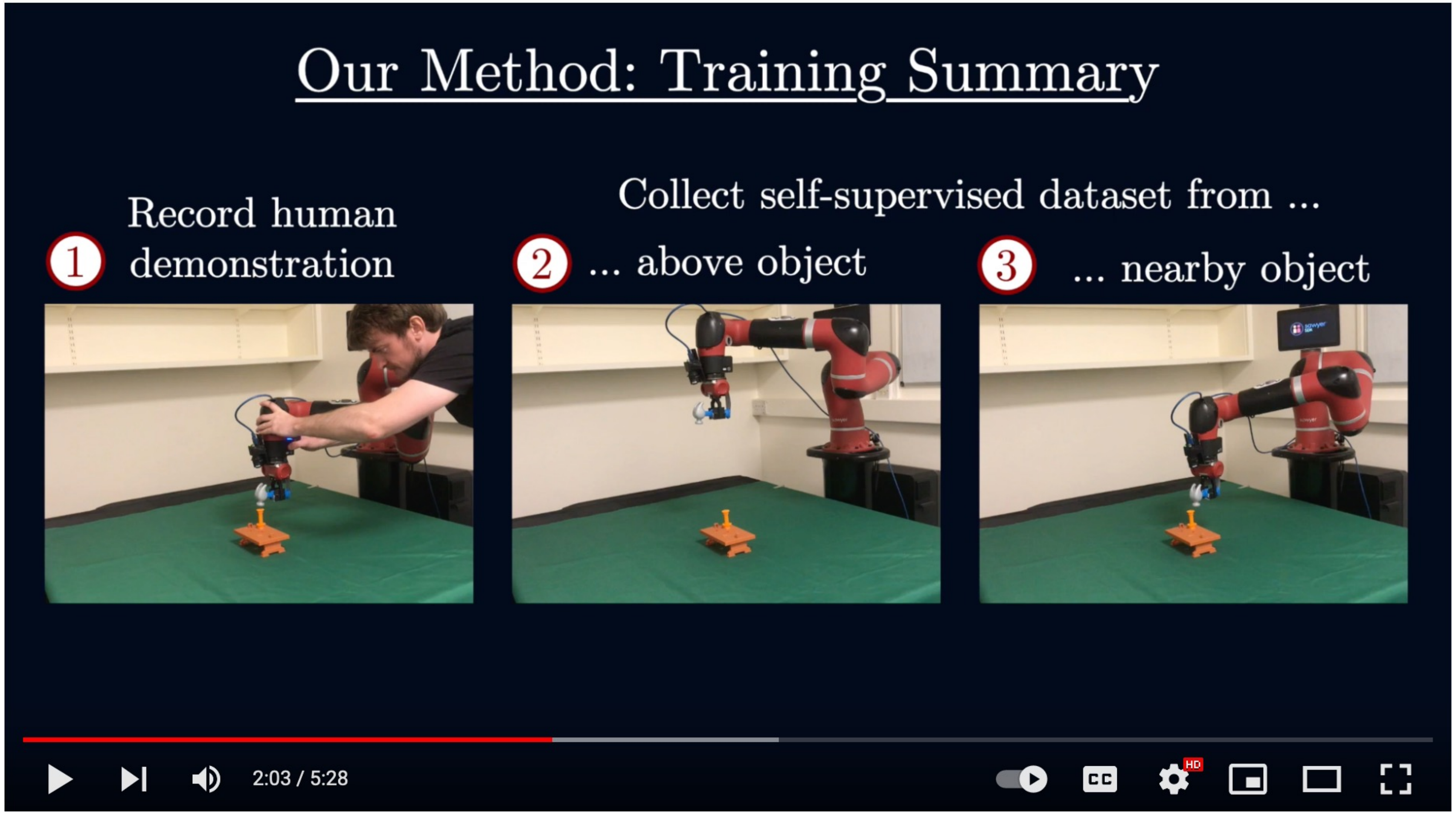


Methods differ in:

- Feature representation: raw pixels/joint angles, or have you already used some other method to learn a deep feature representation?
- Training criterion: classification (discrete actions), or regression (continuous actions)?

Hussein et al. Imitation Learning: A Survey of Learning Methods, 2018.

Example: Coarse-to-Fine Imitation Learning



Edward Johns, [Coarse-to-Fine Imitation Learning: Robot Manipulation from a Single Demonstration](), 2021.

Outline

- Imitation learning: learn the optimal policy by imitating a human
- Deep Q learning: compute Q(s,a) using a neural network
- Actor-Critic learning: The critic is deep-Q, while the actor just learns how to act

Review: Q-Learning

- Q(s,a) – the “quality” of an action

$$Q(s,a) = R(s) + \gamma \sum_{s'} P(s'|s,a)U(s')$$

$$U(s) = \max_{a \in A(s)} Q(s,a)$$

- Q-learning
- Off-policy learning: TD

$$Q_{local}(s_t, a_t) = R_t(s_t) + \gamma \max_{a' \in A(s_{t+1})} Q_t(s_{t+1}, a')$$

$$Q_{t+1}(s_t, a_t) = Q_t(s_t, a_t) + \alpha\big(Q_{local}(s_t, a_t) - Q_t(s_t, a_t)\big)$$

- On-policy learning: SARSA

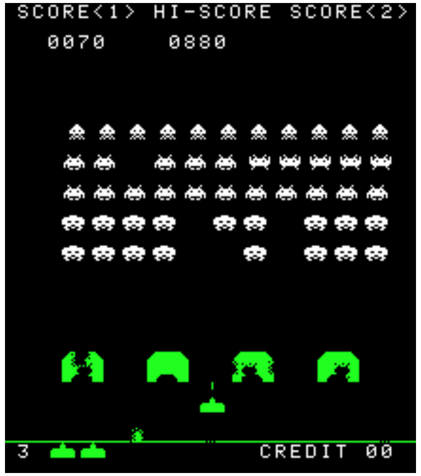
$$a_{t+1} = \pi_t(s_{t+1})$$

$$Q_{local}(s_t, a_t) = R_t(s_t) + \gamma Q_t(s_{t+1}, a_{t+1})$$

Deep Q learning: Discrete actions

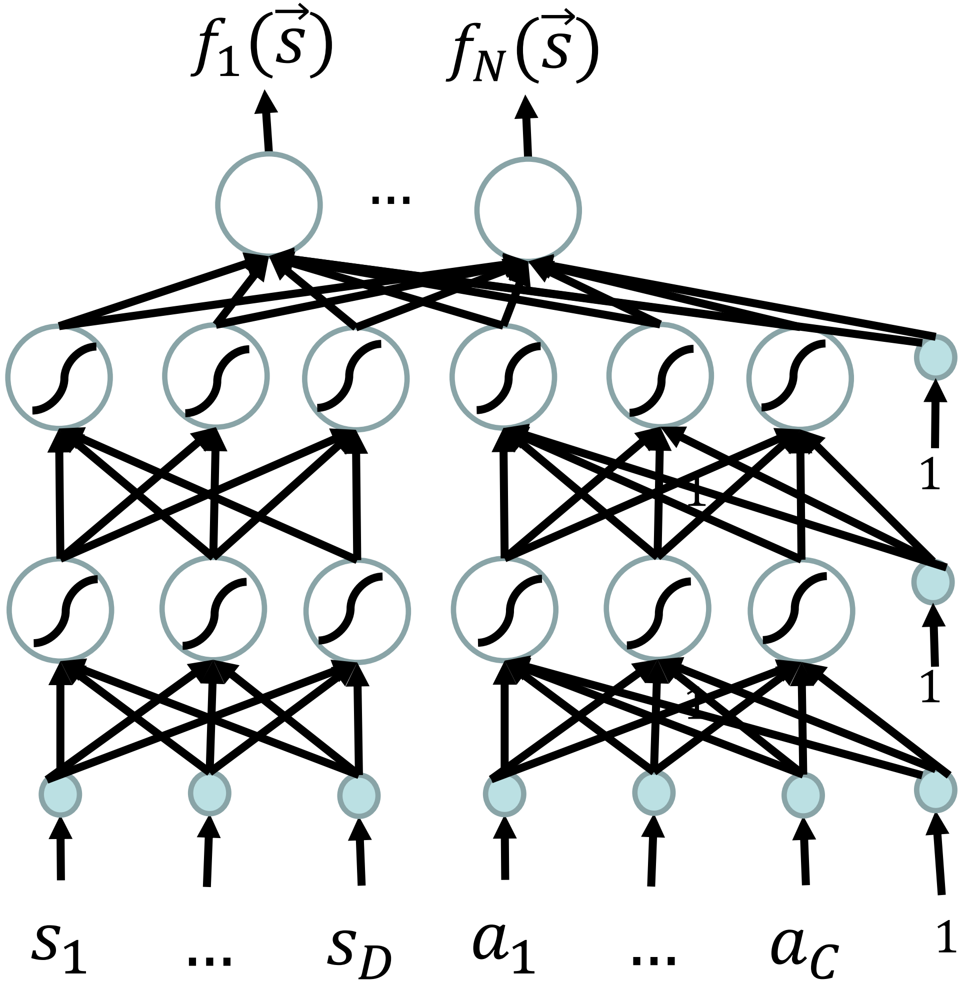
Instead of discrete s, suppose $\vec{s}$ is a vector of real numbers, e.g., the image from the robot's eye camera:

$$\vec{s} = [s_1, \ldots, s_D] =$$



Copyright Taito.

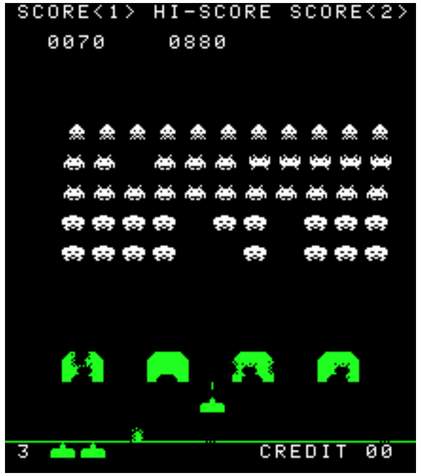
IDeep Q-learning uses a neural network to compute an estimate $f_a(\vec{s})$ which is as close as possible to $Q(\vec{s}, a)$.



Deep Q learning: Continuous actions

Instead of discrete s, suppose $\vec{s}$ is a vector of real numbers, e.g., the image from the robot's eye camera:

$$\vec{s} = [s_1, \ldots, s_D] =$$

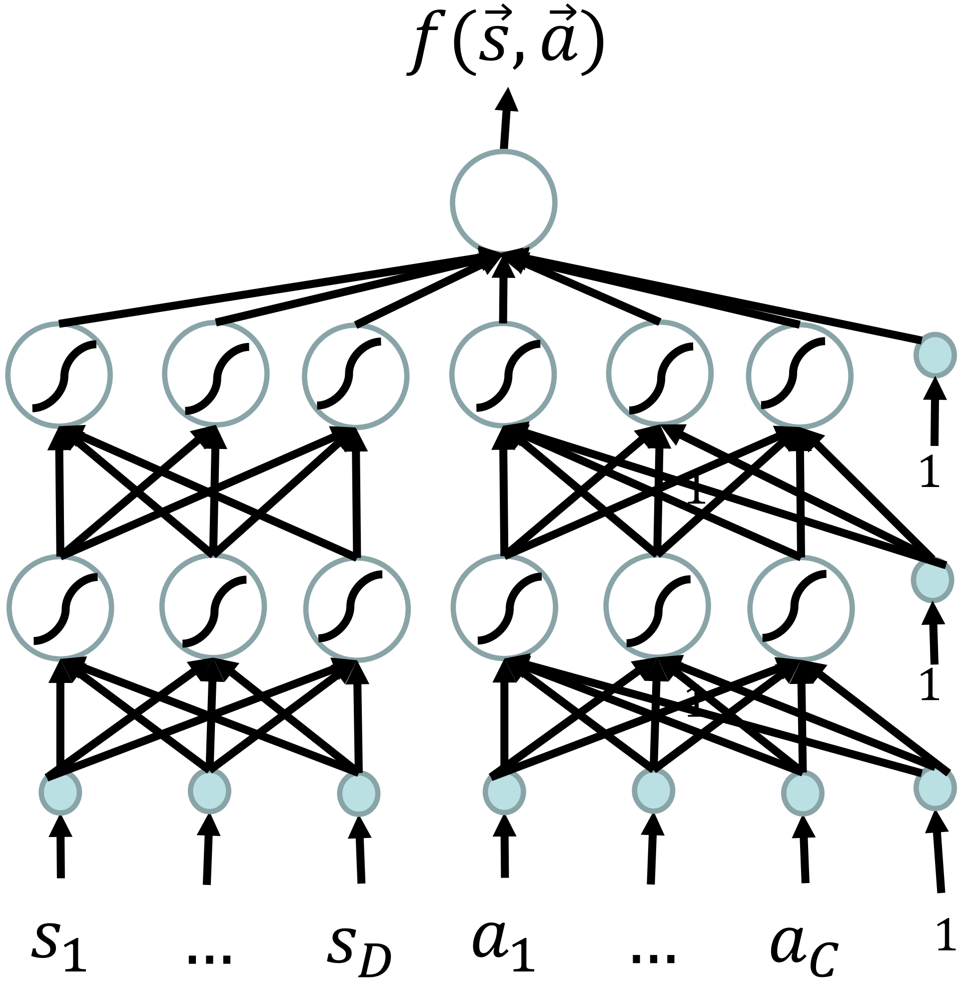


Copyright Taito.

Instead of discrete a, suppose $\vec{a}$ is a vector, e.g., cannon angle and velocity,

$$\vec{a} = [a_1, \ldots, a_C]$$

Deep Q-learning uses a neural network to compute an estimate $f(\vec{s}, \vec{a})$ which is as close as possible to $Q(\vec{s}, \vec{a})$.



MMSE Deep Q learning

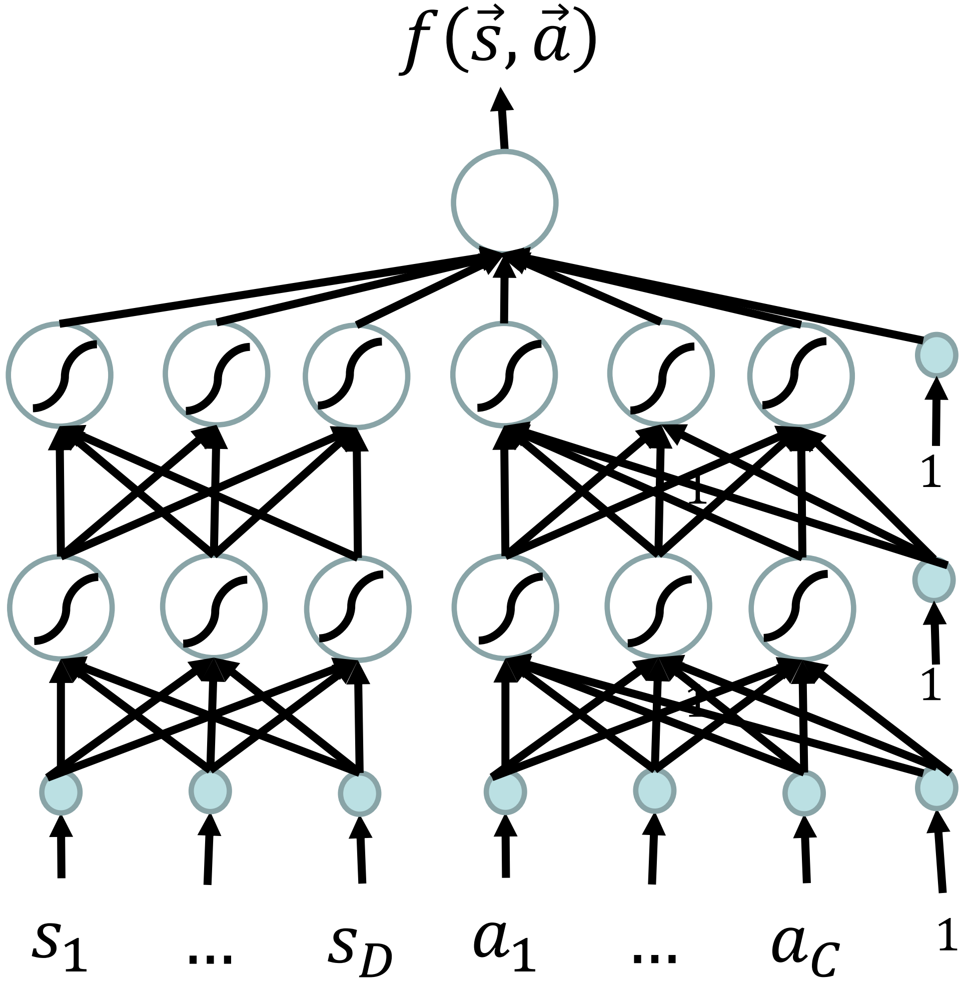
Suppose we train the neural network weights in order to minimize the mean-squared error (MMSE):

$$\mathcal{L} = \frac{1}{2} E[(f(\vec{s}, \vec{a}) - Q(\vec{s}, \vec{a})\ )^2]$$

(where I'm using $E[\cdot]$ as a lazy way to write "average over all training runs of the game").

Then, for each weight w, we update as

$$w \leftarrow w - \eta \frac{d\mathcal{L}}{dw}$$

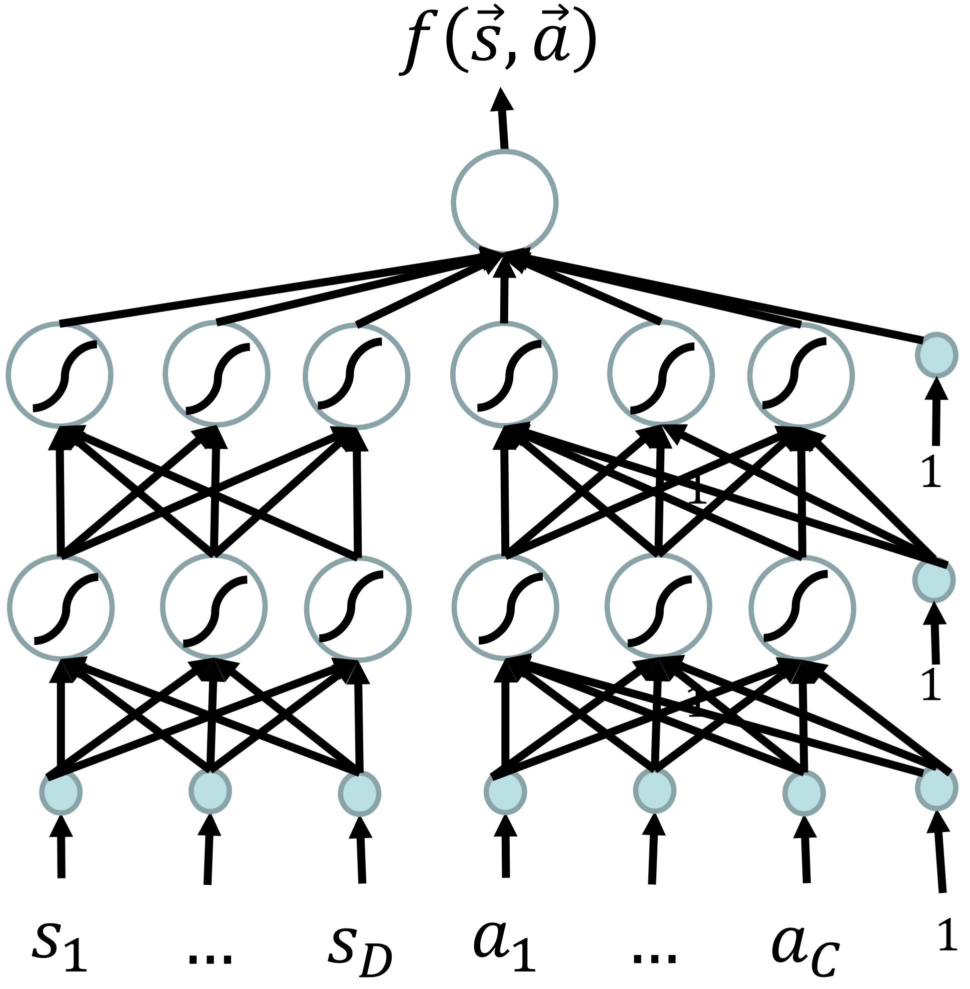


What makes deep Q learning harder than normal neural network training

- We don't know the true value of $Q(\vec{s}, \vec{a})$ for ***<u>any</u>*** of the training runs!

- $Q(\vec{s}, \vec{a})$ is defined to be the expected value of performing action $\vec{a}$. We never know its true expected value: all we know is whether we won or lost that particular game.

- So we can't compute $\mathcal{L}$, and we can't compute $\frac{d\mathcal{L}}{dw}$, and we can't update w!



The solution: Q_{local}

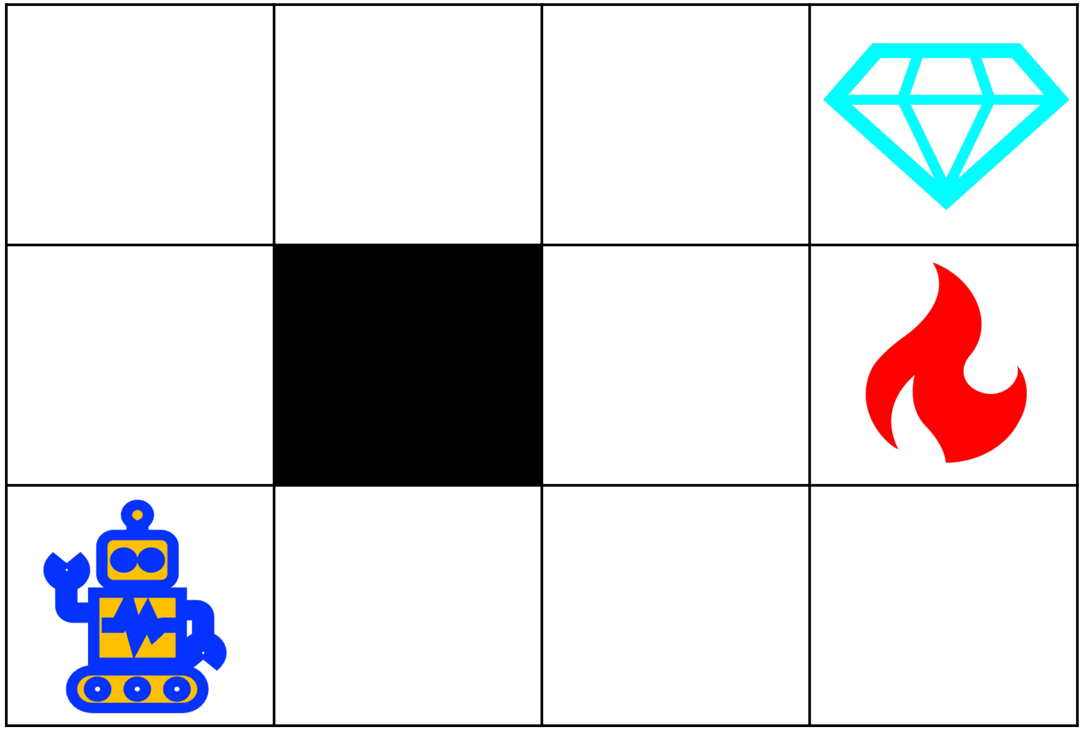
Remember that Q learning was defined as

$$Q_{t+1}(s_t, a_t) \\ = Q_t(s_t, a_t) + \alpha\big(Q_{local}(s_t, a_t) - Q_t(s_t, a_t)\big)$$

where $Q_{local}(s_t, a_t)$ is defined, e.g., in TD as

$$Q_{local}(s_t, a_t) = R_t(s_t) + \gamma \max_{a\prime} Q_t(s_{t+1}, a')$$

…for s_{t+1} equal to the next state we reach after action a_t on **<u>this particular game</u>**.



The solution: Q_{local}

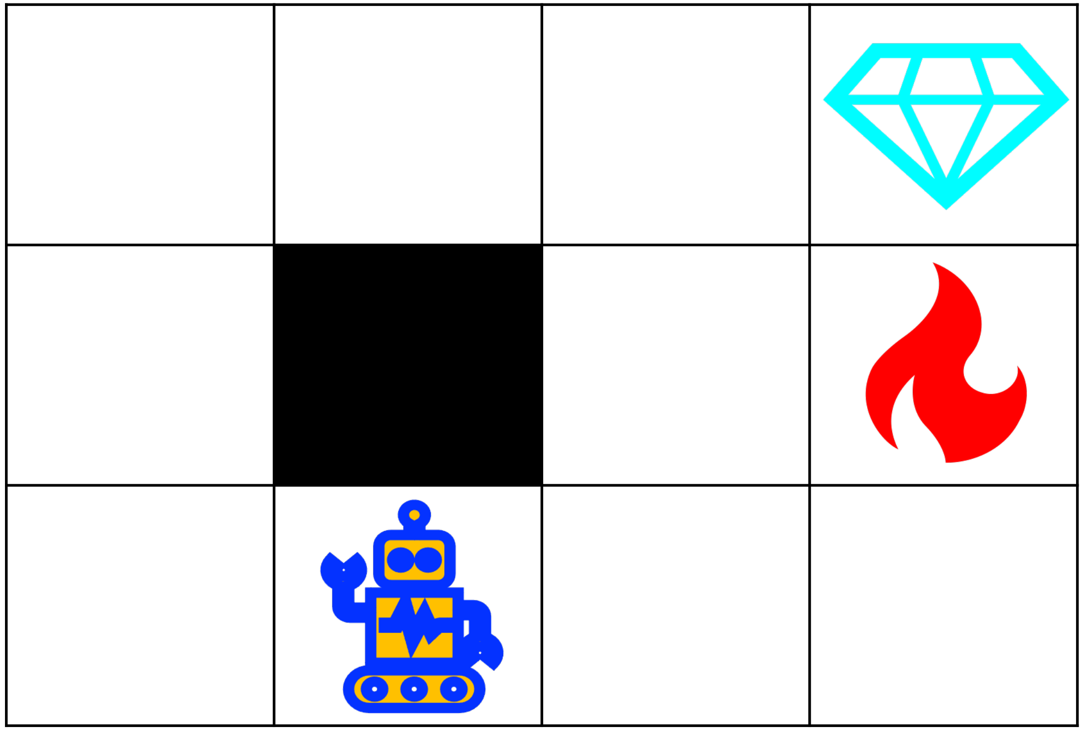
Let's define deep Q learning using the same Q_{local}:

$$\mathcal{L} = \frac{1}{2} E[(f(\vec{s}_t, \vec{a}_t) - Q_{local}(\vec{s}_t, \vec{a}_t)\ )^2]$$

where $Q_{local}(\vec{s}_t, \vec{a}_t)$ is:

$$Q_{local}(\vec{s}_t, \vec{a}_t) = R_t(\vec{s}_t) + \gamma \max_{\vec{a}'} f(\vec{s}_{t+1}, \vec{a}')$$

Now we have an L that depends only on things we know ($f(\vec{s}_t, \vec{a}_t)$, $R_t(\vec{s}_t)$, and $f(\vec{s}_{t+1}, \vec{a}')$), so it can be calculated, differentiated, and used to update the neural network.



Dealing with training instability

- Challenges
  - Target values are not fixed
  - Successive experiences are correlated and dependent on the policy
  - Policy may change rapidly with slight changes to parameters, leading to drastic change in data distribution
- Solutions
  - Freeze target Q network
  - Use *experience replay*

Experience replay

- At each time step:
  - Take action $\vec{a}_t$ according to epsilon-greedy policy
  - Store experience $(\vec{s}_t, \vec{a}_t, r_{t+1}, \vec{s}_{t+1})$ in *replay memory buffer*

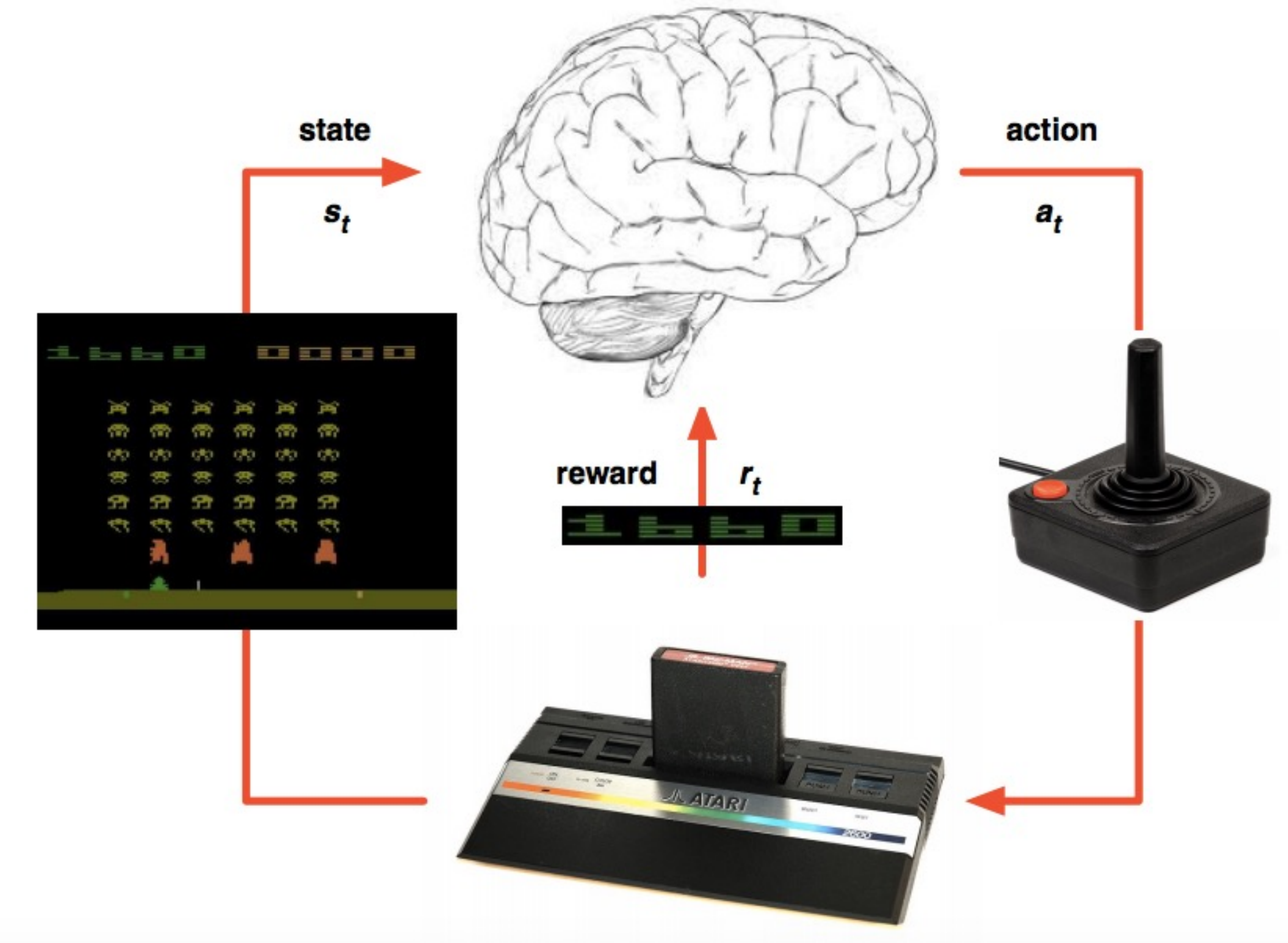
$(\vec{s}_1, \vec{a}_1, r_2, \vec{s}_2)$
$(\vec{s}_2, \vec{a}_2, r_3, \vec{s}_3)$
...

$(\vec{s}_t, \vec{a}_t, r_{t+1}, \vec{s}_{t+1})$

- Learning:
  - Randomly sample a minibatch, $\mathcal{D}$, from the replay buffer.

$\mathcal{D}$ =randomly sampled set of tuples

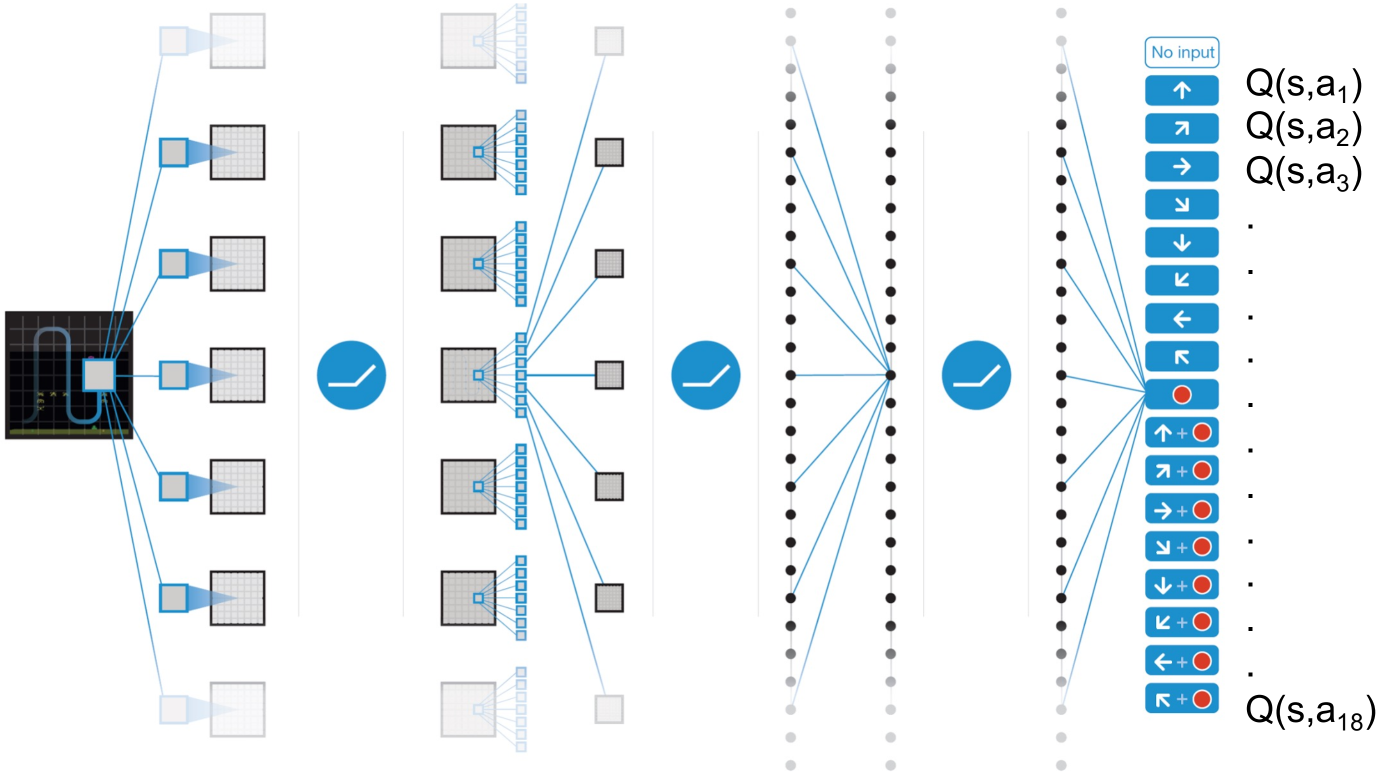
Deep Q learning in Atari



Mnih et al. Human-level control through deep reinforcement learning, *Nature* 2015

Deep Q learning in Atari

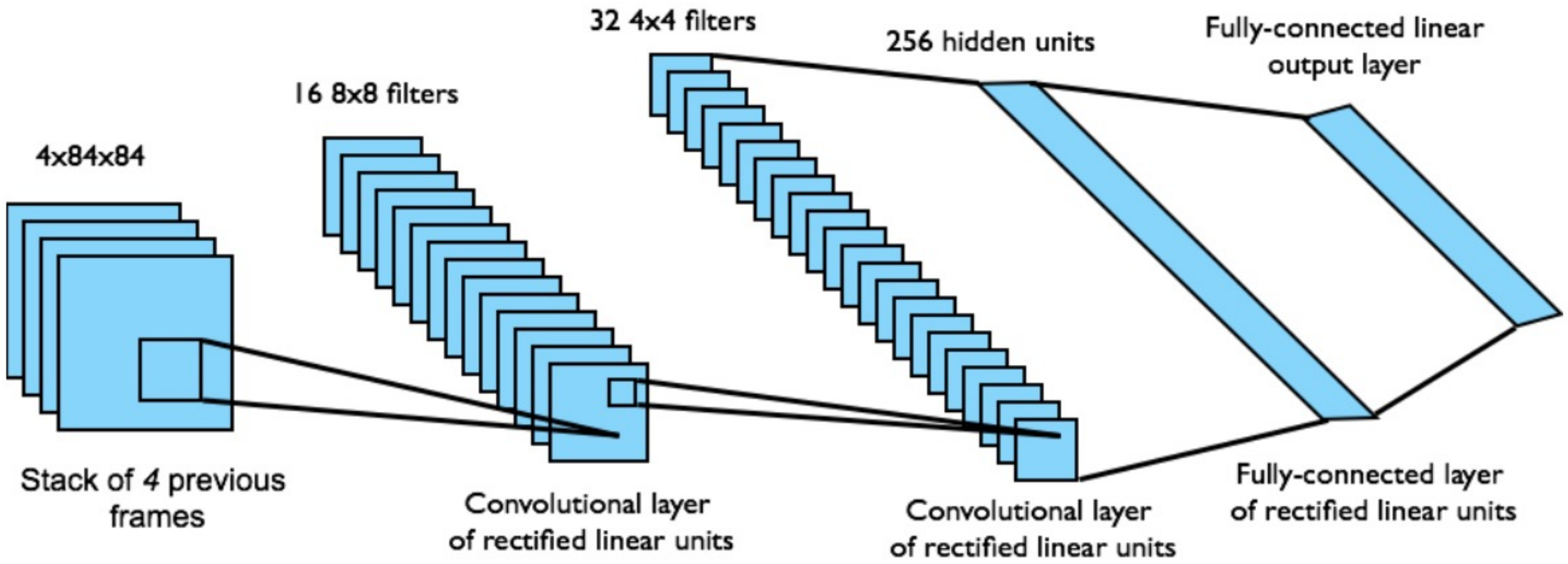
- End-to-end learning of Q(s,a) from pixels s
- Output is Q(s,a) for 18 joystick/button configurations
- Reward is change in score for that step



Mnih et al. Human-level control through deep reinforcement learning, *Nature* 2015

Deep Q learning in Atari

- Input state s is stack of raw pixels from last 4 frames
- Network architecture and hyperparameters fixed for all games



Mnih et al. Human-level control through deep reinforcement learning, *Nature* 2015

Deep Q learning in Atari

Deep Q-Learning Playing Atari Breakout

Outline

- Imitation learning: learn the optimal policy by imitating a human
- Deep Q learning: compute Q(s,a) using a neural network
- Actor-Critic learning: The critic is deep-Q, while the actor just learns how to act

Two approaches to deep reinforcement learning

- Deep Q learning: train a network to estimate Q(s,a)
  - Like value iteration: we focus on Q(s,a), which is closely related to U(s)
  - Big problem: Q(s,a) is very noisy, needs lots of smoothing
- Imitation learning: train a network to imitate a human being
  - Like policy iteration: focus directly on estimating $\pi(s)$
  - Big problem: the only way to train this is by imitating a human!

The Actor-Critic Algorithm

- Deep Q-learning gives us a network Q(s,a) which is very noisy, so we don't really want to trust it
- A policy network can directly estimate $\pi(s)$. The only problem is that we have no way to train it, unless we imitate human behavior.

Actors from the Comédie Française, by Antoine Watteau, 1720. Public Domain, https://commons.wikimedia.org/w/index.php?curid=15418670

Actor-critic algorithm

So let's train two neural nets!

- $Q_t(s,a)$ is the **critic**, and is trained according to the deep Q-learning algorithm (MMSE).
- $\pi_a(s)$ is the **actor**, and is trained to satisfy the critic

The Critic, by Lajos Tihanyi. Oil on canvas, 1916. Public Domain, https://commons.wikimedia.org/w/index.php?curid=17837438

The Actor-Critic Algorithm

Main idea:

- The **actor** is a policy network that decides what action to perform:

  $\pi_a(s) =$ Probability that a is the best action in state s

- The **critic** is a deep Q-learning network that estimates the quality of that action ($Q(s,a)$).

  $Q(s,a) =$ Expected sum of future rewards if (s,a)

- The critic is noisy, so they don't get to decide the action. Instead, we only use the critic to help us to train the actor.

The Actor-Critic Algorithm

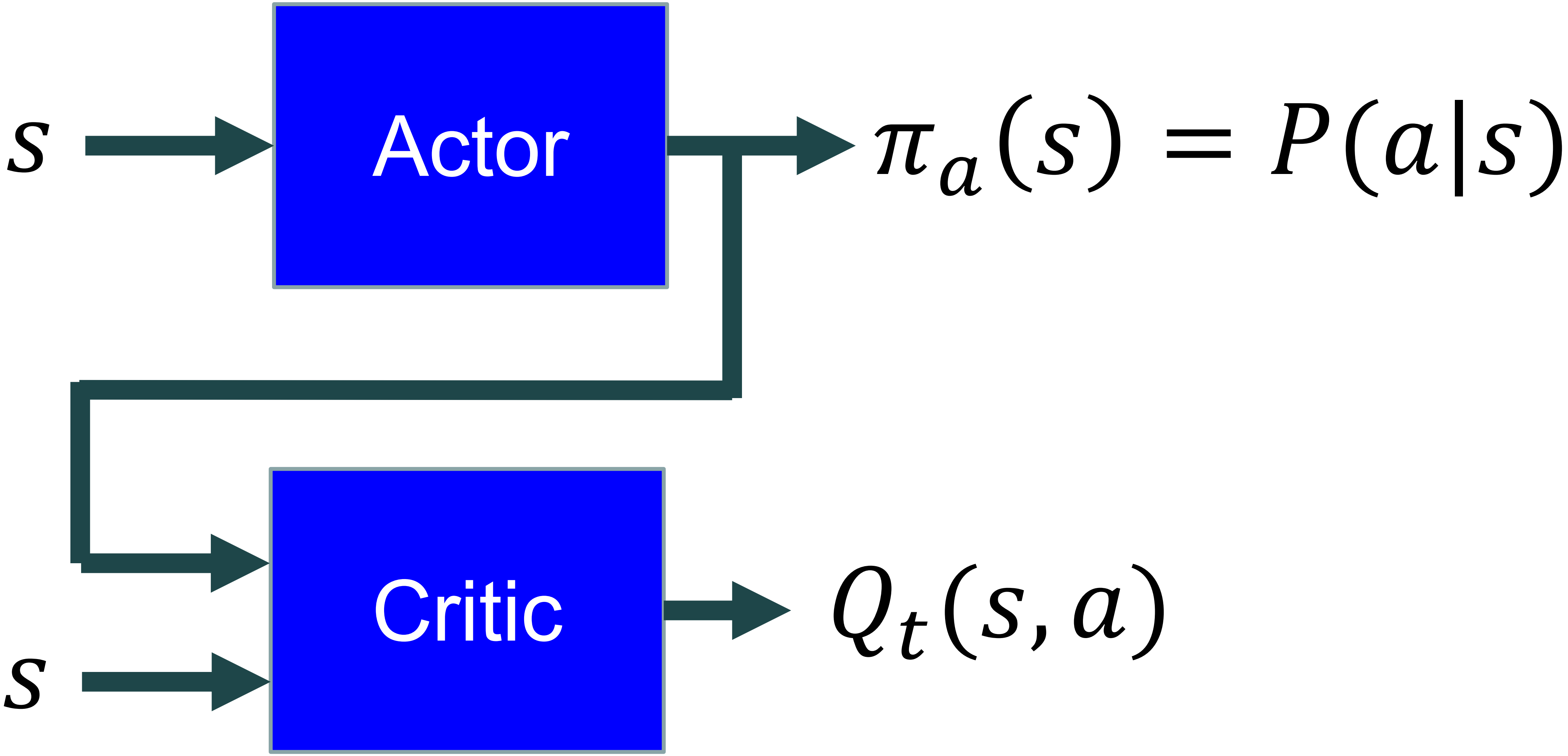
$$\pi_a(s) = \text{Probability that } a \text{ is the best action in state } s$$
$$Q(s,a) = \text{Expected sum of future rewards if } (s,a)$$

- The critic is noisy, so they don't get to decide the action. Instead, we only use the critic to help us to train the actor.

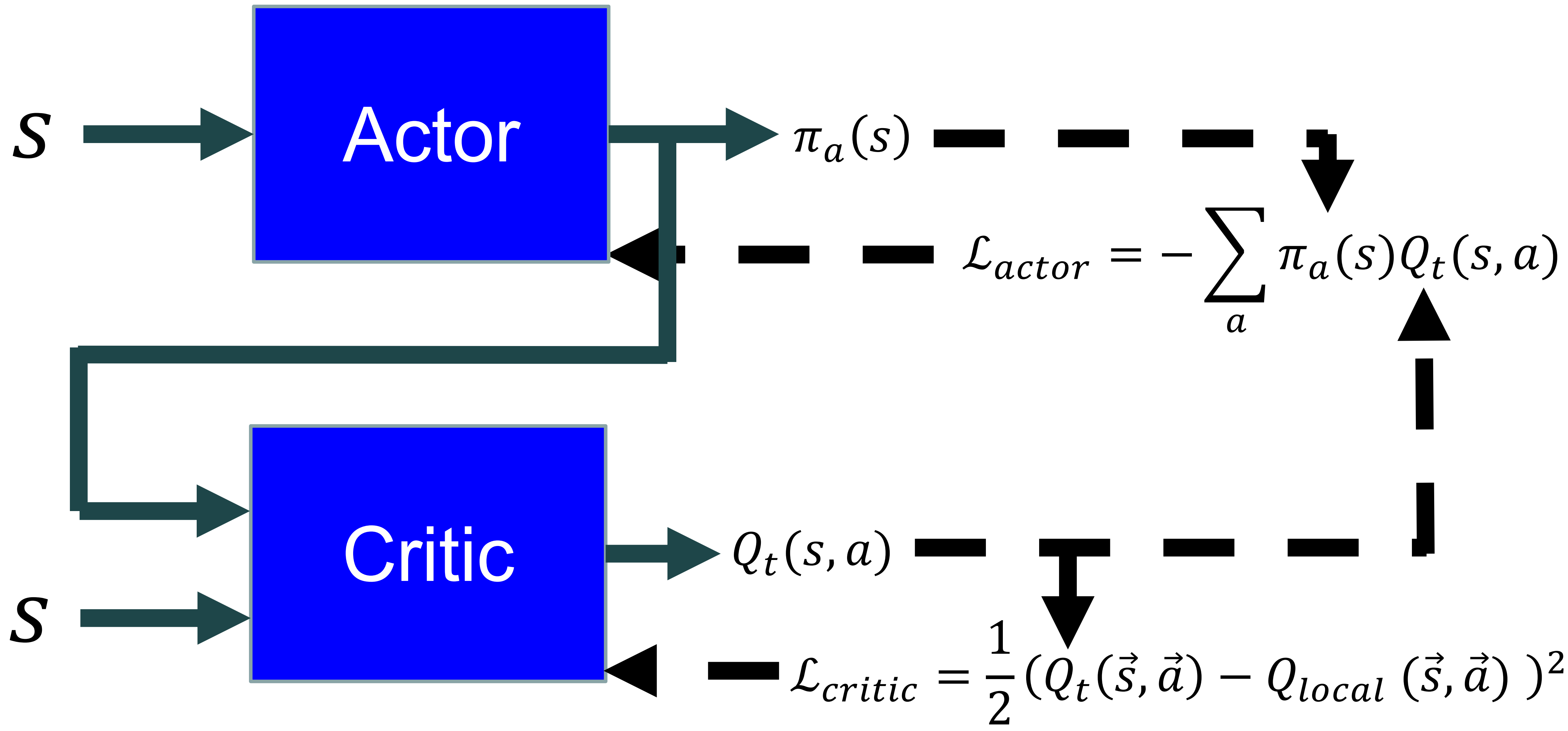
$$\mathcal{L} = -\sum_a \pi_a(s) Q(s,a)$$

- The training loss = negative expected sum of future rewards given action a, averaged over the probability with which the actor chooses action a.

The Actor-Critic Algorithm: Forward-Prop



The Actor-Critic Algorithm: Back-Prop



Asynchronous advantage actor-critic (A3C)

TORCS car racing simulation video

Mnih et al. Asynchronous Methods for Deep Reinforcement Learning. ICML 2016

Overview: All of the Model-Free Reinforcement Learning Algorithms You've Learned

- Policy learning: learn $\pi(s)$ directly
  - Imitation learning
- Q-learning: learn $Q(s,a) = R(s) + \gamma \sum_{s'} P(s'|s,a)U(s')$
  - Table-based: TD, SARSA
  - Deep Q-learning
- Actor-Critic: learn both