

Lecture 10: Deep Q-learning

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Contents and Goals

- How we can make Q-learning work with deep networks
 - Use replay buffers, separate target networks
- Tricks for improving Q-learning in practice
 - Double Q-learning, multi-step Q-learning
- Continuous Q-learning methods
- Goals
 - Understand how to implement Q-learning so that it can be used with complex function approximators
 - Understand how to extend Q-learning to continuous actions

Table of Contents

1 Q-learning with deep neural networks

- Problem 1: Correlated samples – Solution 1: Replay buffers
- Problem 2: Moving target – Solution 2: Target networks

2 Deep deterministic policy gradient (DDPG)

- Continuous action space
- Approximate the optimal policy using another network

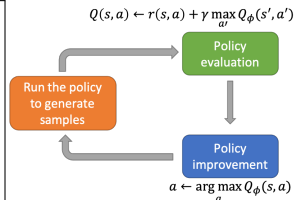
3 Extensions

- Double Q-learning
- Multi-step returns
- Practical tips and examples

Review: Fitted Q-iteration (FQI)

- Full fitted Q-iteration algorithm. Loop:
 1. collect dataset $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy π loop for K iterations:
 2. set $y_i \leftarrow r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$
 3. set $\phi \leftarrow \arg \min_\phi \sum_i \|Q_\phi(s_i, a_i) - y_i\|^2$

- Online fitted Q-iteration algorithm. Loop:
 1. observe one sample (s_i, a_i, r_i, s'_i) using behavior policy π
 2. set $y_i \leftarrow r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$
 3. set $\phi \leftarrow \phi - \alpha \frac{dQ_\phi(s_i, a_i)}{d\phi} (Q_\phi(s_i, a_i) - y_i)$



Problem 1: Correlated samples in MDPs

- Online fitted Q-iteration algorithm. Loop:

1. take some action a_i observe (s_i, a_i, r_i, s'_i)
2. set $y_i \leftarrow r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$
3. set $\phi \leftarrow \phi - \alpha \frac{dQ_\phi(s_i, a_i)}{d\phi} (Q_\phi(s_i, a_i) - y_i)$

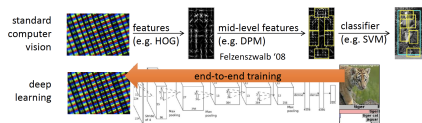
- these samples are correlated!
- Fitted Q-iteration is not gradient descent!

$$\phi \leftarrow \phi - \alpha \frac{dQ_\phi(s_i, a_i)}{d\phi} \left(Q_\phi(s_i, a_i) - \underbrace{\left(r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i) \right)}_{\text{no gradient through target value!}} \right)$$

Review: Supervised learning vs. Sequential decision-making

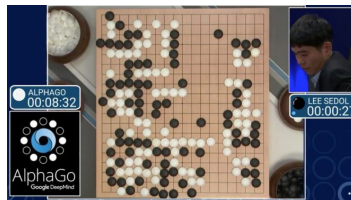
Supervised learning

- Samples are independent and identically distributed (i.i.d.)
- Given an input, map an optimal output



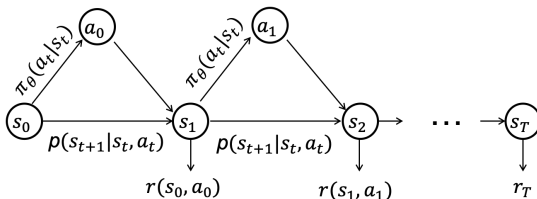
Reinforcement learning

- Samples are not i.i.d., temporally correlated
- Given an initial state, find a sequence of optimal actions



Correlated samples in online Q-learning

- Online fitted Q-iteration algorithm. Loop:
 1. take some action a_i , observe (s_i, a_i, r_i, s'_i)
 2. set $\phi \leftarrow \phi - \alpha \frac{dQ_\phi(s_i, a_i)}{d\phi} (Q_\phi(s_i, a_i) - (r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)))$
- sequential states are strongly correlated
- target value is always changing



Correlate samples

- Full fitted Q-iteration algorithm. Loop:
 1. collect **dataset** $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy π
loop for K iterations:
 2. set $y_i \leftarrow r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$
 3. set $\phi \leftarrow \arg \min_\phi \sum_i \|Q_\phi(s_i, a_i) - y_i\|^2$

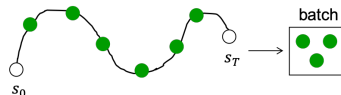
- Online fitted Q-iteration. Loop:
 1. take some action a_i , observe (s_i, a_i, r_i, s'_i)
 2. set $y_i = r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$
 3. set $\phi \leftarrow \phi - \alpha \frac{dQ_\phi(s_i, a_i)}{d\phi} (Q_\phi(s_i, a_i) - y_i)$

special case with $K = 1$,
and one gradient step

How to reduce the correlation between samples?

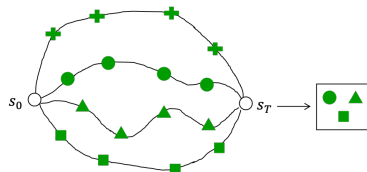
- Samples in a single episode:

- temporally correlated



- Samples from different episodes:

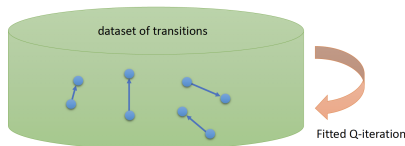
- i.i.d



Replay buffers: store the data/transitions

- Full fitted Q-iteration algorithm. Loop:
 1. collect **dataset** $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy π loop for K iterations:
 2. set $y_i \leftarrow r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$
 3. set $\phi \leftarrow \arg \min_\phi \sum_i \|Q_\phi(s_i, a_i) - y_i\|^2$

- any behavior policy π will work!
- just load data from a **buffer** here
- still use $K = 1$ and one gradient step



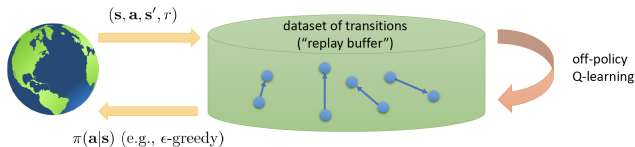
Q-learning with a replay buffer

- Loop:

1. sample a batch $\{(s_j, a_j, r_j, s'_j)\}$ from buffer \mathcal{B}

2. $\phi \leftarrow \phi - \alpha \sum_i \frac{dQ_\phi(s_j, a_j)}{d\phi} \left(Q_\phi(s_j, a_j) - \left(r_j + \gamma \max_{a'_j} Q_\phi(s'_j, a'_j) \right) \right)$

- Step 1: samples are no longer correlated if they come from different episodes
- Step 2: use **multiple samples** in the batch for low-variance gradient
- **Question:** Where does the data come from?
 - Need to periodically feed the replay buffer



Full Q-learning with a replay buffer

- Loop:

1. collect dataset $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy, add it to \mathcal{B}
loop for K iterations:
2. sample a batch $\{(s_j, a_j, r_j, s'_j)\}$ from buffer \mathcal{B}
3. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_\phi(s_j, a_j)}{d\phi} \left(Q_\phi(s_j, a_j) - \left(r_j + \gamma \max_{a'_j} Q_\phi(s'_j, a'_j) \right) \right)$

- $K = 1$ is common, though larger K is more efficient

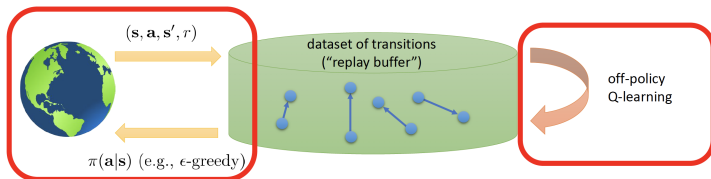


Table of Contents

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3 Extensions

- Double Q-learning
- Multi-step returns
- Practical tips and examples

Problem 2: Moving target in the Bellman equation

- Online fitted Q-iteration algorithm. Loop:

1. take some action a_i observe (s_i, a_i, r_i, s'_i)
2. set $y_i \leftarrow r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$
3. set $\phi \leftarrow \phi - \alpha \frac{dQ_\phi(s_i, a_i)}{d\phi} (Q_\phi(s_i, a_i) - y_i)$

- Samples are correlated: solved by a replay buffer

- Fitted Q-iteration is not gradient descent!

- Target value changes when the Q-network ϕ is updated!

$$\phi \leftarrow \phi - \alpha \frac{dQ_\phi(s_i, a_i)}{d\phi} \left(Q_\phi(s_i, a_i) - \underbrace{\left(r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i) \right)}_{\text{no gradient through target value!}} \right)$$

The moving target

- Full Q-learning with a replay buffer. Loop:

1. collect dataset $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy, add it to \mathcal{B}
loop for K iterations:

2. sample a batch $\{(s_j, a_j, r_j, s'_j)\}$ from buffer \mathcal{B}

3.
$$\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_\phi(s_j, a_j)}{d\phi} \underbrace{\left(Q_\phi(s_j, a_j) - \left(r_j + \gamma \max_{a'_j} Q_\phi(s'_j, a'_j) \right) \right)}_{\text{one gradient step, moving target}}$$

- Full fitted Q-iteration algorithm. Loop:

1. collect dataset $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy π
loop for K iterations:

2. set $y_i \leftarrow r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$

3. set
$$\phi \leftarrow \arg \min_{\phi} \underbrace{\sum_i ||Q_\phi(s_i, a_i) - y_i||^2}_{\text{perfectly well-defined, stable regression}}$$

Solution 2: Target networks

- Idea: use another Q-network and fix it in the inner loop
 - Targets don't change in the inner loop

Q-learning with replay buffer and target network. Loop:

1. save target network parameters: $\phi' \leftarrow \phi$

loop for N iterations:

2. collect dataset $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy, add it to \mathcal{B}

loop for K iterations:

3. sample a batch $\{(s_j, a_j, r_j, s'_j)\}$ from buffer \mathcal{B}

4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_\phi(s_j, a_j)}{d\phi} \left(Q_\phi(s_j, a_j) - \left(r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j) \right) \right)$

“Classic” deep Q-network (DQN)

Q-learning with replay buffer and target network. Loop:

1. save target network parameters: $\phi' \leftarrow \phi$

loop for N iterations:

2. collect dataset $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy, add it to \mathcal{B}

loop for K iterations:

3. sample a batch $\{(s_j, a_j, r_j, s'_j)\}$ from buffer \mathcal{B}

4.
$$\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_{\phi}(s_j, a_j)}{d\phi} \left(Q_{\phi}(s_j, a_j) - \left(r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j) \right) \right)$$

- Classic deep Q-learning with $K = 1$. Loop:

1. take some action a_i and observe (s_i, a_i, s'_i, r_i) , add it to \mathcal{B}

2. sample mini-batch $\{(s_j, a_j, r_j, s'_j)\}$ from \mathcal{B} uniformly

3. compute $y_j = r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j)$ using target network $Q_{\phi'}$

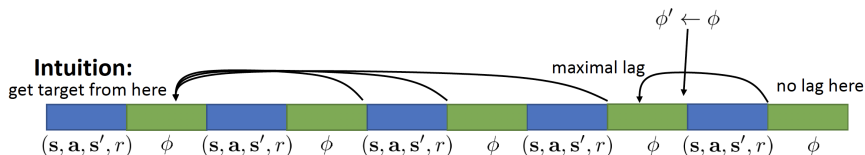
4.
$$\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_{\phi}(s_j, a_j)}{d\phi} (Q_{\phi}(s_j, a_j) - y_j)$$

5. update ϕ' : copy ϕ every N steps

Alternative target network

- Classic deep Q-learning with $K = 1$. Loop:
 1. take some action a_i and observe (s_i, a_i, s'_i, r_i) , add it to \mathcal{B}
 2. sample mini-batch $\{(s_j, a_j, r_j, s'_j)\}$ from \mathcal{B} uniformly
 3. compute $y_j = r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j)$ using target network $Q_{\phi'}$
 4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_{\phi}(s_j, a_j)}{d\phi} (Q_{\phi}(s_j, a_j) - y_j)$
 5. **update ϕ' : copy ϕ every N steps**

- **Problem:** In one inner loop, time lags for different steps are different!



Alternative target network

- Classic deep Q-learning with $K = 1$. Loop:
 1. take some action a_i and observe (s_i, a_i, s'_i, r_i) , add it to \mathcal{B}
 2. sample mini-batch $\{(s_j, a_j, r_j, s'_j)\}$ from \mathcal{B} uniformly
 3. compute $y_j = r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j)$ using target network $Q_{\phi'}$
 4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_{\phi}(s_j, a_j)}{d\phi} (Q_{\phi}(s_j, a_j) - y_j)$
 5. update ϕ' : copy ϕ every N steps

- Feels weirdly uneven, can we always have the same lag?
- Popular alternative updating for the target network:

5. update $\phi' : \phi' \leftarrow \tau \phi' + (1 - \tau)\phi$

- $\tau = 0.99$ works well

Deep Q-learning and fitted Q-iteration

Deep Q-learning ($N = 1, K = 1$). Loop:

1. save target network parameters: $\phi' \leftarrow \phi$

loop for N iterations:

2. collect M transitions $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy, add them to \mathcal{B}

loop for K iterations:

3. sample a batch $\{(s_j, a_j, r_j, s'_j)\}$ from buffer \mathcal{B}

4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_\phi(s_j, a_j)}{d\phi} \left(Q_\phi(s_j, a_j) - \left(r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j) \right) \right)$

Fitted Q-iteration (written similarly as above). Loop:

1. collect M transitions $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy, add them to \mathcal{B}

loop for N iterations:

2. save target network parameters: $\phi' \leftarrow \phi$

loop for K iterations:

3. sample a batch $\{(s_j, a_j, r_j, s'_j)\}$ from buffer \mathcal{B}

4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_\phi(s_j, a_j)}{d\phi} \left(Q_\phi(s_j, a_j) - \left(r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j) \right) \right)$

A more general view

Deep Q-learning ($N = 1, K = 1$). Loop:

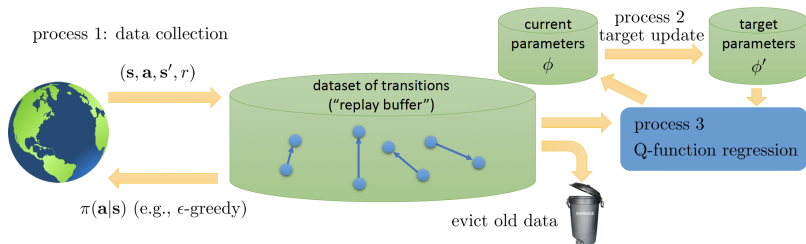
1. save target network parameters: $\phi' \leftarrow \phi$

loop for N iterations:

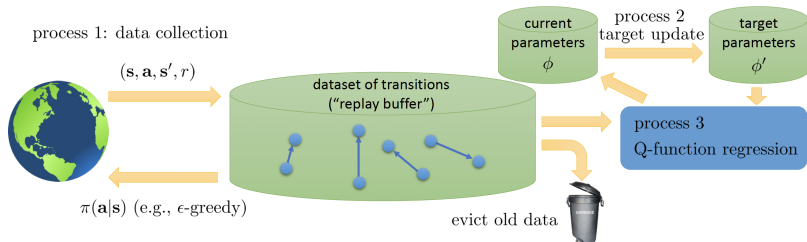
2. collect M transitions $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy, add them to \mathcal{B}
loop for K iterations:

3. sample a batch $\{(s_j, a_j, r_j, s'_j)\}$ from buffer \mathcal{B}

4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_\phi(s_j, a_j)}{d\phi} \left(Q_\phi(s_j, a_j) - \left(r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j) \right) \right)$



A more general view



- Online fitted Q-iteration: evict immediately, process 1, process 2, and process 3 run at the same speed
- DQN: process 1 and process 3 run at the same speed, process 2 is slow
- Fitted Q-iteration: process 3 is in the inner loop of process 2, which is in the inner loop of process 1

Table of Contents

- 1 Q-learning with deep neural networks
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What's the problem with continuous actions?

- Full fitted Q-iteration algorithm. Loop:

1. collect dataset $\{(s_i, a_i, r_i, s'_i)\}$ using behavior policy π
loop for K iterations:
 2. set $y_i \leftarrow r_i + \gamma \max_{a'_i} Q_\phi(s'_i, a'_i)$
 3. set $\phi \leftarrow \arg \min_\phi \sum_i \|Q_\phi(s_i, a_i) - y_i\|^2$

- Classic deep Q-learning. Loop:

1. take some action a_i and observe (s_i, a_i, s'_i, r_i) , add it to \mathcal{B}
2. sample mini-batch $\{(s_j, a_j, r_j, s'_j)\}$ from \mathcal{B} uniformly
3. compute $y_j = r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j)$ using target network $Q_{\phi'}$
4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_\phi(s_j, a_j)}{d\phi} (Q_\phi(s_j, a_j) - y_j)$
5. update ϕ' : copy ϕ every N steps

The target value involves the max operator

- Classic deep Q-learning. Loop:

1. take some action a_i and observe (s_i, a_i, s'_i, r_i) , add it to \mathcal{B}
2. sample mini-batch $\{(s_j, a_j, r_j, s'_j)\}$ from \mathcal{B} uniformly
3. compute $y_j = r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j)$ using target network $Q_{\phi'}$
4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_{\phi}(s_j, a_j)}{d\phi} (Q_{\phi}(s_j, a_j) - y_j)$
5. update ϕ' : copy ϕ every N steps

$$\pi(a|s) = \begin{cases} 1 & \text{if } a = \arg \max_a Q_{\phi}(s, a) \\ 0 & \text{otherwise} \end{cases}$$

- target value $y_j = r_j + \gamma \max_{a'_j} Q_{\phi'}(s'_j, a'_j)$
 - particularly problematic, need another inner loop of optimization
 - **Question**: how to perform the optimization, i.e., the max operator?

Option 1: Stochastic optimization

- The action space is typically low-dimensional
 - What about stochastic optimization?

The simplest solution: uniform sampling

- $\max_a Q(s, a) \approx \max\{Q(s, a_1), \dots, Q(s, a_n)\}$
- (a_1, \dots, a_n) sampled from the some distribution (e.g., uniform)

+ dead simple
+ efficiently parallelizable
-not very accurate

More accurate solution: Cross-entropy method (CEM)

Simple **iterative** stochastic optimization:

1. Draw a sample from a probability distribution
2. Minimize the cross-entropy between this distribution and a target distribution to produce a better sample in the next iteration

works OK, for up to about 40 dimensions

A simple example of maximizing $f(\mathbf{x})$. Loop:

1. Obtain N samples: $\mathbf{X} \sim \text{SampleGaussian}(\mu, \sigma^2; N)$
2. Evaluate objective function $f(\mathbf{X})$ at sampled points
3. Sort \mathbf{X} by $f(\mathbf{X})$ in descending order: $\mathbf{X} \leftarrow \text{sort}(\mathbf{X}, f)$
4. Update sampling distribution by the top M elites:
 $\mu \leftarrow \text{mean}(\mathbf{X}(1:M)), \quad \sigma^2 \leftarrow \text{var}(\mathbf{X}(1:M))$

Objective:

$$\begin{aligned} \mathbf{x}^* &= \arg \max_{\mathbf{x}} f(\mathbf{x}) \\ &\Downarrow \\ \mathbf{a}^* &= \arg \max_{\mathbf{a}} Q(s, \mathbf{a}) \end{aligned}$$

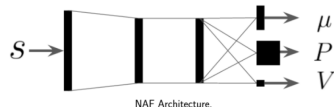
Many stochastic optimization solutions...

- Covariance matrix adaptation evolution strategy (CMA-ES)
 - an evolutionary algorithm for difficult non-linear non-convex black-box optimization problems in continuous domain
- Many more solutions...

Option 2: Easily maximizable Q-functions

- Use function class that is easy to optimize
 - e.g., the quadratic function

$$Q_{\phi}(s, a) = -\frac{1}{2}(a - \mu_{\phi}(s))^T P_{\phi}(s)(a - \mu_{\phi}(s)) + V_{\phi}(s)$$



- **NAF: Normalized Advantage Functions**

$$\arg \max_a Q_{\phi}(s, a) = \mu_{\phi}(s)$$

$$\max_a Q_{\phi}(s, a) = V_{\phi}(s)$$

- + no change to algorithm
- + just as efficient as Q-learning
- loses representational power

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- 1 Q-learning with deep neural networks
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Option 3: learn an approximate maximizer

- Lillicrap et al., “Continuous control with deep reinforcement learning,” ICLR 2016.
 - Deep deterministic policy gradient (DDPG)
 - Really approximate **deep Q-learning** in the continuous action domain
- $\max_a Q_\phi(s, a) = Q_\phi(s, \arg \max_a Q_\phi(s, a))$
- **idea**: train another network $\mu_\theta(s)$ such that

$$\mu_\theta(s) \approx \arg \max_a Q_\phi(s, a)$$

- **Question**: how to optimize this deterministic “actor” $\mu_\theta(s)$?

Q-learning with continuous actions

- **idea:** train another network $\mu_\theta(s)$ such that

$$\mu_\theta(s) \approx \arg \max_a Q_\phi(s, a)$$

- how? just solve $\theta \leftarrow \arg \max_\theta Q_\phi(s, \mu_\theta(s))$

$$\frac{dQ_\phi(s, \mu_\theta(s))}{d\theta} = \frac{dQ_\phi}{da} \cdot \frac{da}{d\theta} = \frac{dQ_\phi}{d\mu_\theta(s)} \cdot \frac{d\mu_\theta(s)}{d\theta}$$

- new target

$$y_j = r_j + \gamma Q_{\phi'}(s'_j, \mu_\theta(s'_j)) \approx r_j + \gamma Q_{\phi'}(s'_j, \arg \max_{a'_j} Q_{\phi'}(s'_j, a'_j))$$

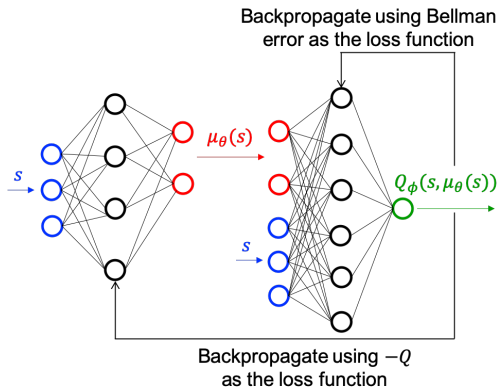
DDPG network architecture

- Backpropagate the critic:

$$\nabla_{\phi} = \frac{dQ_{\phi}(s, a)}{d\phi} (Q_{\phi}(s, a) - y)$$

- Backpropagate the actor:

$$\nabla_{\theta} = \frac{dQ_{\phi}}{d\mu_{\theta}(s)} \cdot \frac{d\mu_{\theta}(s)}{d\theta}$$



Deep deterministic policy gradient (DDPG)

- Loop:

1. take some action a_i and observe (s_i, a_i, s'_i, r_i) , add it to \mathcal{B}
2. sample mini-batch $\{(s_j, a_j, r_j, s'_j)\}$ from \mathcal{B} uniformly
3. compute $y_j = r_j + \gamma Q_{\phi'}(s'_j, \mu_{\theta'}(s'_j))$ by target networks $Q_{\phi'}$ and $\mu_{\theta'}$
4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_{\phi}(s_j, a_j)}{d\phi} (Q_{\phi}(s_j, a_j) - y_j)$
5. $\theta \leftarrow \theta + \beta \sum_j \frac{dQ_{\phi}}{d\mu_{\theta}(s_j)} \frac{d\mu_{\theta}(s_j)}{d\theta}$
6. update ϕ', θ' : $\phi' \leftarrow \tau\phi' + (1 - \tau)\phi$, $\theta' \leftarrow \tau\theta' + (1 - \tau)\theta$

- The behavior policy π :

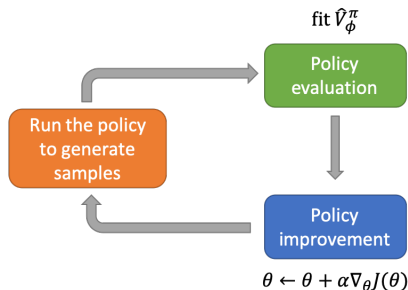
- The target greedy policy is $\pi^*(s) = \mu_{\theta}(s)$, actually
- Add some exploration noise to the target greedy policy, just like ϵ -greedy in tabular Q-learning

$$\pi(a|s) \sim \mathcal{N}(\mu_{\theta}(s), \sigma^2)$$

Review: Actor-critic algorithms

- Loop:

1. sample $\{s_i, a_i, r_i, s'_i\}$ from $\pi_\theta(a|s)$ (run it on the robot)
2. **policy evaluation**: fit $\hat{V}_\phi^\pi(s)$ to sampled reward sums
3. evaluate $\hat{A}^\pi(s_i, a_i) = r_i + \gamma \hat{V}_\phi^\pi(s'_i) - \hat{V}_\phi^\pi(s_i)$
4. **policy improvement**: $\nabla_\theta J(\theta) \approx \sum_i \nabla_\theta \log \pi_\theta(a_i|s_i) \hat{A}^\pi(s_i, a_i)$
5. $\theta \leftarrow \theta + \alpha \nabla_\theta J(\theta)$



DDPG vs. Actor-critic

- DDPG. Loop:

1. take some action a_i and observe (s_i, a_i, s'_i, r_i) , add it to \mathcal{B}
2. sample mini-batch $\{(s_j, a_j, r_j, s'_j)\}$ from \mathcal{B} uniformly
3. compute $y_j = r_j + \gamma Q_{\phi'}(s'_j, \mu_{\theta'}(s'_j))$ by target networks $Q_{\phi'}$ and $\mu_{\theta'}$
4. $\phi \leftarrow \phi - \alpha \sum_j \frac{dQ_{\phi}(s_j, a_j)}{d\phi} (Q_{\phi}(s_j, a_j) - y_j)$
5. $\theta \leftarrow \theta + \beta \sum_j \frac{dQ_{\phi}}{d\mu_{\theta}(s_j)} \frac{d\mu_{\theta}(s_j)}{d\theta}$
6. update ϕ', θ' : $\phi' \leftarrow \tau\phi' + (1 - \tau)\phi$, $\theta' \leftarrow \tau\theta' + (1 - \tau)\theta$

- Actor-critic. Loop:

1. sample $\{s_i, a_i, r_i, s'_i\}$ from $\pi_{\theta}(a|s)$ (run it on the robot)
2. policy evaluation: fit $\hat{V}_{\phi}^{\pi}(s)$ to sampled reward sums
3. evaluate $\hat{A}^{\pi}(s_i, a_i) = r_i + \gamma \hat{V}_{\phi}^{\pi}(s'_i) - \hat{V}_{\phi}^{\pi}(s_i)$
4. policy improvement: $\nabla_{\theta} J(\theta) \approx \sum_i \nabla_{\theta} \log \pi_{\theta}(a_i | s_i) \hat{A}^{\pi}(s_i, a_i)$
5. $\theta \leftarrow \theta + \alpha \nabla_{\theta} J(\theta)$

Review: Q-learning vs. SARSA

$$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha[R_{t+1} + \gamma \max_a Q(S_{t+1}, a) - Q(S_t, A_t)]$$

- Q-learning approximates the optimal action-value function for an optimal policy, $Q \approx Q_* = Q_{\pi_*}$
 - The target policy is greedy w.r.t Q , $\pi(a|s) = \arg \max_a Q(s, a)$
 - The behavior policy can be others, e.g., $b(a|s) = \varepsilon$ -greedy
-

$$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha[R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t)]$$

- SARSA approximates the action-value function for the behavior policy, $Q \approx Q_\pi = Q_b$
 - The target and the behavior policy are the same, e.g., $\pi(a|s) = b(a|s) = \varepsilon$ -greedy

DDPG vs. Actor-critic

- DDPG

- The actor: approximate the optimal policy
$$a^* \mu_\theta(s) = \arg \max_a Q_\phi(s, a)$$
- The critic: approximate the optimal action-value function Q_ϕ^*
- Off-policy, more sample efficient

- Actor-critic

- The actor: approximate the current policy $a \sim \pi_\theta(a|s)$
- The critic: approximate the state-value function V_ϕ^π for given policy π
- On-policy, at least converge to a local optimum

Table of Contents

- 1 Q-learning with deep neural networks
 - Problem 1: Correlated samples – Solution 1: Replay buffers
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- 2 Deep deterministic policy gradient (DDPG)
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 - Approximate the optimal policy using another network
- 3 Extensions
 - Double Q-learning
 - Multi-step returns
 - Practical tips and examples

Overestimation in Q-learning

- target value $y_j = r_j + \gamma \underbrace{\max_{a'_j} Q_{\phi'}(s'_j, a'_j)}_{\text{this is the problem}}$

- Imagine we have two random variables: x_1 and x_2

$$\mathbb{E}[\max(x_1, x_2)] \geq \max(\mathbb{E}[x_1], \mathbb{E}[x_2])$$

- $Q_{\phi'}(s', a')$ is not perfect – it looks “noisy”
- hence $\max_{a'} Q_{\phi'}(s', a')$ **overestimates** the next value!
- note that $\max_{a'} Q_{\phi'}(s', a') = Q_{\phi'}(s', \arg \max_{a'} Q_{\phi'}(s', a'))$
 - action selected according to $Q_{\phi'}$
 - value also comes from $Q_{\phi'}$

Double Q-learning

- $\mathbb{E}[\max(x_1, x_2)] \geq \max(\mathbb{E}[x_1], \mathbb{E}[x_2])$
- note that $\max_{a'} Q_{\phi'}(s', a') = Q_{\phi'}(s', \arg \max_{a'} Q_{\phi'}(s', a'))$
 - action selected according to $Q_{\phi'}$
 - value also comes from $Q_{\phi'}$
 - if the noise in the two parts is decorrelated, the problem goes away!
- **IDEA:** don't use the same network to choose the action and evaluate value!
- “double” Q-learning: use two networks

$$Q_{\phi_A}(s, a) \leftarrow r + \gamma Q_{\phi_B}(s', \arg \max_{a'} Q_{\phi_A}(s', a'))$$

$$Q_{\phi_B}(s, a) \leftarrow r + \gamma Q_{\phi_A}(s', \arg \max_{a'} Q_{\phi_B}(s', a'))$$

- if the two Q-networks, Q_{ϕ_A} and Q_{ϕ_B} , are noisy in different ways, there is no problem

Double Q-learning in practice

- Where to get two Q-functions?
 - just use the current and target networks!
- standard Q-learning: $y = r + \gamma Q_{\phi'}(s', \arg \max_{a'} Q_{\phi'}(s', a'))$
- double Q-learning: $y = r + \gamma Q_{\phi'}(s', \arg \max_{a'} Q_{\phi}(s', a'))$
 - just use **current network** (not target network) to evaluate action
 - still use target network to evaluate value

Table of Contents

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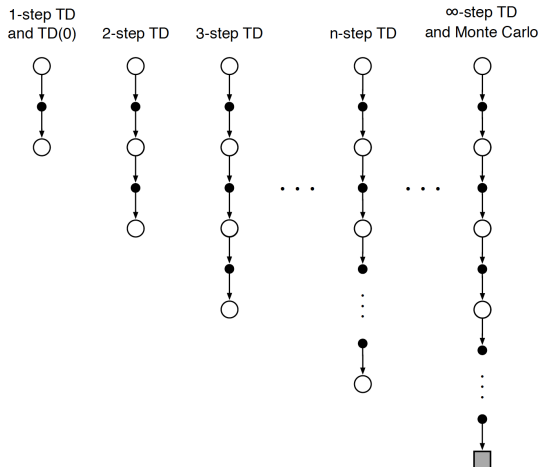
n -step bootstrapping: Combine MC and one-step TD

- Neither MC or one-step TD is always the best, we generalize both methods so that one can shift from one to the other smoothly as needed to meet the demands of a particular task
- One-step TD: In many applications, one wants to be able to update the action very fast to take into account anything that has changed
- However, bootstrapping works best if it is over a length of time in which a significant and recognizable state change has occurred

$n = 1$	n -step TD	$n = \infty$
TD(0)	\longleftrightarrow	MC

n -step TD prediction

- Perform an update based on an intermediate number of rewards, more than one, but less than all of them until termination



Recall MC and TD(0) updates

- In MC updates, the target is the **complete return**

$$G_t = R_{t+1} + \gamma R_{t+2} + \dots + \gamma^{T-t+1} R_T$$

$$\begin{aligned} V(S_t) &\leftarrow V(S_t) + \alpha[G_t - V(S_t)] \\ &= V(S_t) + \alpha[R_{t+1} + \gamma R_{t+2} + \dots + \gamma^{T-t+1} R_T - V(S_t)] \end{aligned}$$

- In TD(0) updates, the target is the **one-step return**

$$G_{t:t+1} = R_{t+1} + \gamma V(S_{t+1})$$

$$\begin{aligned} V(S_t) &\leftarrow V(S_t) + \alpha[G_{t:t+1} - V(S_t)] \\ &= V(S_t) + \alpha[R_{t+1} + \gamma V(S_{t+1}) - V(S_t)] \end{aligned}$$

n -step TD update rule

- For n -step TD, set the target as the **n -step return**

$$G_{t:t+n} = R_{t+1} + \gamma R_{t+2} + \dots + \gamma^{n-1} R_{t+n} + \gamma^n V(S_{t+n})$$

- All n -step returns can be considered approximations to the complete return, truncated after n steps and then corrected for the remaining missing terms by $V(S_{t+n})$

$$\begin{aligned} V(S_t) &\leftarrow V(S_t) + \alpha[G_{t:t+n} - V(S_t)] \\ &= V(S_t) + \alpha[R_{t+1} + \gamma R_{t+2} + \dots + \gamma^{n-1} R_{t+n} + \gamma^n V(S_{t+n}) - V(S_t)] \end{aligned}$$

Deep Q-learning with n -step bootstrapping

- Q-learning target: $y_{j,t} = r_{j,t} + \gamma \max_{a'_{j,t+1}} Q_{\phi'}(s'_{j,t+1}, a'_{j,t+1})$
 - these are the only values that matter if $Q_{\phi'}$ is bad!
 - these values are important if $Q_{\phi'}$ is good
- Construct multi-step targets, N -step return estimator:

$$y_{j,t} = \sum_{t'=t}^{t+N-1} \gamma^{t'-t} r_{j,t'} + \gamma^N \max_{a'_{j,t+N}} Q_{\phi'}(s'_{j,t+N}, a'_{j,t+N})$$

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Simple practical tips for Q-learning

- Q-learning takes some care to stabilize
 - Test on easy, reliable tasks first, make sure your implementation is correct

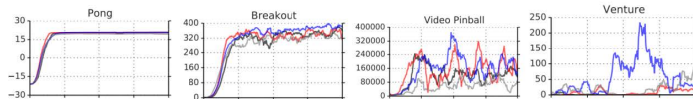


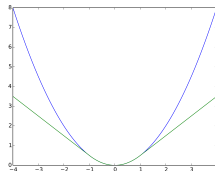
Figure: From T. Schaul, J. Quan, I. Antonoglou, and D. Silver. "Prioritized experience replay". *arXiv preprint arXiv:1511.05952* (2015), Figure 7

- Large replay buffers help improve stability
 - Looks more like fitted Q-iteration
- It takes time, be patient - might be no better than random for a while
- Start with high exploration and gradually move to high exploitation

Advanced tips for Q-learning

- Bellman error gradients can be big; clip gradients or use Huber loss

$$\mathcal{L}(x) = \begin{cases} x^2/2 & \text{if } |x| \leq \delta \\ \delta|x| - \delta^2/2 & \text{otherwise} \end{cases}$$



- Double Q-learning *helps a lot* in practice, simple and no downsides
- N -step returns also help a lot, but have some downsides
- Schedule exploration (high to low) and learning rates (high to low)
 - Adam optimizer can help too
- Run multiple random seeds, it's very inconsistent between runs

Q-learning with convolutional networks

- Mnih et al., “Human-level control through deep reinforcement learning,” 2013.
- Use replay buffer and target network
- One-step backup, one gradient step
- Can be improved a lot with double Q-learning (and other tricks)



Space Invaders



Boxing



Skiing



Alien



Carnival



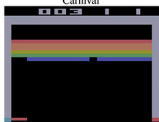
Pong



River Raid



Montezuma's Revenge



Breakout



Kung-Fu Master



Enduro



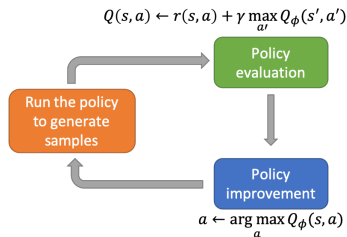
Ms. PacMan

Q-learning on a real robot

- Gu et al., “Robot manipulation with deep reinforcement learning and ...,” 2017.
- Continuous actions with NAF (quadratic in actions)
- Use replay buffer and target network
- One-step backup, four gradient steps per simulator step for efficiency
- Parallelized across multiple robots



- Q-learning with deep neural networks
 - Replay buffers
 - Target networks
- Generalized fitted Q-iteration
- Deep deterministic policy network
 - Deep Q-learning for continuous action space
 - Another network for approximating optimal policy
 - Off-policy
- Extensions
 - Double Q-learning
 - Multi-step Q-learning



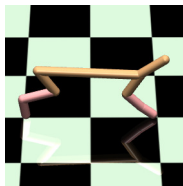
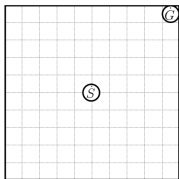
Learning objectives of this lecture

- You should be able to...
 - Use deep neural networks to approximate Q-functions, be able to implement deep Q-learning with replay buffers and target networks
 - Use deep deterministic policy gradient for continuous actions
 - Know double Q-learning for addressing the overestimation problem
 - Know deep Q-learning with n -step returns

- Lecture 8 of CS285 at UC Berkeley, **Deep Reinforcement Learning, Decision Making, and Control**
 - <http://rail.eecs.berkeley.edu/deeprlcourse/static/slides/lec-8.pdf>
- DRL Q-learning papers
 - Mnih et al. (2013). **Human level control through deep reinforcement learning**: Q-learning with convolutional networks for playing Atari.
 - Van Hasselt, Guez , Silver. (2015). **Deep reinforcement learning with double Q-learning**: a very effective trick to improve performance of deep Q-learning.
 - Lillicrap et al. (2016). **Continuous control with deep reinforcement learning**: continuous Q-learning with actor network for approximate maximization.
 - Wang, Schaul , Hessel, van Hasselt, Lanctot , de Freitas (2016). **Dueling network architectures for deep reinforcement learning**: separates value and advantage estimation in Q-function.
 - Z. Ren, et al., **Self-Paced Prioritized Curriculum Learning With Coverage Penalty in Deep Reinforcement Learning**, *TNNLS*, 2018.

Homework 2

- Study the DDPG algorithm in detail
- Implement the DDPG algorithm on problems 1 & 2
 - Problem 1: the point maze navigation, continuous state-action space ($s, a \in \mathbb{R}^2$, $s \in [-0.5, 0.5]^2$, $a \in [-0.1, 0.1]^2$)
 - Problem 2: the MuJoCo HalfCheetah, make the robot run forward
 - Compare DDPG with policy gradient and actor-critic algorithms
- Write a report introducing the algorithms and your experimentation
 - Explanations, steps, evaluation results, visualizations...
 - Submit the code and the report to zicanhu@smail.nju.edu.cn



THE END