Function Approximation, Deep Q Network

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Until now, we have solved the tasks by explicitly calculating expected return, either as $v(s)$ or as $q(s, a)$.

- Finite number of states and actions.
- We do not share information between different states or actions.
- We use $q(s, a)$ if we do not have the environment model (a model-free method); if we do, it is usually better to estimate $v(s)$ and choose actions as $\arg\max_a \mathbb{E}[R + v(s')]$.

The methods we know differ in several aspects:

- Whether they compute return by simulating a whole episode (Monte Carlo methods), or by bootstrapping (temporal difference, i.e., $G_t \approx R_t + v(S_t)$, possibly $n$-step).
  - TD methods are more noisy and unstable, but can learn immediately and explicitly assume Markovian property of value function.

- Whether they estimate the value function of the same policy they use to generate the episodes (on-policy) or not (off-policy).
  - The off-policy methods are more noisy and unstable, but more flexible.
Function Approximation

We now approximate the value function $v$ and/or the state-value function $q$, selecting it from a family of functions parametrized by a weight vector $w \in \mathbb{R}^d$.

We denote the approximations as

$$\hat{v}(s; w),$$
$$\hat{q}(s, a; w).$$

Weights are usually shared among states. Therefore, we need to define state distribution $\mu(s)$ to obtain an objective for finding the best function approximation (if we give preference to some states, improving their estimates might worsen estimates in other states).

The state distribution $\mu(s)$ gives rise to a natural objective function called **Mean Squared Value Error**, denoted $\overline{VE}$:

$$\overline{VE}(w) \overset{\text{def}}{=} \sum_{s \in S} \mu(s) \left( v_\pi(s) - \hat{v}(s; w) \right)^2.$$
Function Approximation

For on-policy algorithms, \( \mu(s) \) is often the on-policy distribution (fraction of time spent in \( s \)).

- For **episodic tasks**, let \( h(s) \) be the probability that an episode starts in state \( s \), and let \( \eta(s) \) denote the number of time steps spent, on average, in state \( s \) in a single episode:

\[
\eta(s) = h(s) + \sum_{s'} \eta(s') \sum_a \pi(a|s') p(s|s', a).
\]

The on-policy distribution is then obtained by normalizing: \( \mu(s) \stackrel{\text{def}}{=} \frac{\eta(s)}{\sum_{s'} \eta(s')} \).

If there is discounting (\( \gamma < 1 \)), it should be treated as a form of termination, by including a factor \( \gamma \) to the second term of the \( \eta(s) \) equation.

- For **continuing tasks**, we require \( \gamma < 1 \), and employ the same definition as in the episodic case.
Gradient and Semi-Gradient Methods

The functional approximation (i.e., the weight vector $w$) is usually optimized using gradient methods, for example as

$$
w_{t+1} \leftarrow w_t - \frac{1}{2} \alpha \nabla w_t \left( v_\pi(S_t) - \hat{v}(S_t; w_t) \right)^2$$

$$\leftarrow w_t + \alpha \left( v_\pi(S_t) - \hat{v}(S_t; w_t) \right) \nabla w_t \hat{v}(S_t; w_t).$$

As usual, the $v_\pi(S_t)$ is estimated by a suitable sample of a return:

- in Monte Carlo methods, we use episodic return $G_t$,
- in temporal difference methods, we employ bootstrapping and use one-step return

$$R_{t+1} + [-\text{done}] \cdot \gamma \hat{v}(S_{t+1}; w)$$

or an $n$-step return.
Gradient Monte Carlo Algorithm for Estimating \( \hat{\nu} \approx \nu_{\pi} \)

Input: the policy \( \pi \) to be evaluated
Input: a differentiable function \( \hat{\nu} : S \times \mathbb{R}^d \rightarrow \mathbb{R} \)
Algorithm parameter: step size \( \alpha > 0 \)
Initialize value-function weights \( \mathbf{w} \in \mathbb{R}^d \) arbitrarily (e.g., \( \mathbf{w} = 0 \))

Loop forever (for each episode):
  Generate an episode \( S_0, A_0, R_1, S_1, A_1, \ldots, R_T, S_T \) using \( \pi \)
  Loop for each step of episode, \( t = 0, 1, \ldots, T - 1 \):
    \( \mathbf{w} \leftarrow \mathbf{w} + \alpha [G_t - \hat{\nu}(S_t, \mathbf{w})] \nabla \hat{\nu}(S_t, \mathbf{w}) \)

Algorithm 9.3 of "Reinforcement Learning: An Introduction, Second Edition".
Linear Methods

A simple special case of function approximation are linear methods, where

\[ \hat{v}(x(s); w) \overset{\text{def}}{=} x(s)^T w = \sum x(s)_i w_i. \]

The \(x(s)\) is a representation of state \(s\), which is a vector of the same size as \(w\). It is sometimes called a feature vector.

The SGD update rule then becomes

\[ w_{t+1} \leftarrow w_t + \alpha (v_\pi(S_t) - \hat{v}(x(S_t); w_t)) x(S_t). \]

This rule is the same as in the tabular methods if \(x(s)\) is the one-hot representation of the state \(s\).
State Aggregation

Simple way of generating a feature vector is **state aggregation**, where several neighboring states are grouped together.

For example, consider a 1000-state random walk, where transitions lead uniformly randomly to any of 100 neighboring states on the left or on the right. Using state aggregation, we can partition the 1000 states into 10 groups of 100 states. Monte Carlo policy evaluation then computes the following:

![Diagram showing state distribution and value scale](image)

*Figure 9.1 of “Reinforcement Learning: An Introduction, Second Edition”.*
Many methods for construction features for linear methods have been developed in the past:

- polynomials,
- Fourier bases,
- radial basis functions,
- tile coding,
- ...

But of course, nowadays we use deep neural networks, which construct a suitable feature vector automatically as a latent variable (the last hidden layer).
If $t$ overlapping tiles are used, the learning rate is usually normalized as $\alpha/t$. 

*Figure 9.9 of “Reinforcement Learning: An Introduction, Second Edition”.*
For example, on the 1000-state random walk example, the performance of the tile coding surpasses state aggregation:

\[ \sqrt{VE} \]

averaged over 30 runs

Each tile covers 200 states, and when multiple tiles are used, they are offset by 4 states.

Figure 9.10 of "Reinforcement Learning: An Introduction, Second Edition".
Asymmetrical Tile Coding

In higher dimensions, the tiles should have asymmetrical offsets, with a sequence of \((1, 3, 5, \ldots, 2d - 1)\) proposed as a good choice.

Figure 9.11 of “Reinforcement Learning: An Introduction, Second Edition”.

Figure 9.11 of “Reinforcement Learning: An Introduction, Second Edition”.
In TD methods, we again bootstrap the estimate \( v_\pi(S_t) \) as \( R_{t+1} + \left[ -\text{done} \right] \cdot \gamma \hat{v}(S_{t+1}; w) \).

### Semi-gradient TD(0) for estimating \( \hat{v} \approx v_\pi \)

**Input:** the policy \( \pi \) to be evaluated

**Input:** a differentiable function \( \hat{v} : S^+ \times \mathbb{R}^d \rightarrow \mathbb{R} \) such that \( \hat{v}(\text{terminal}, \cdot) = 0 \)

**Algorithm parameter:** step size \( \alpha > 0 \)

**Initialize** value-function weights \( w \in \mathbb{R}^d \) arbitrarily (e.g., \( w = 0 \))

**Loop for each episode:**
- **Initialize** \( S \)
- **Loop for each step of episode:**
  - Choose \( A \sim \pi(\cdot | S) \)
  - Take action \( A \), observe \( R, S' \)
  - \( w \leftarrow w + \alpha \left[ R + \gamma \hat{v}(S', w) - \hat{v}(S, w) \right] \nabla \hat{v}(S, w) \)
  - \( S \leftarrow S' \)
- until \( S \) is terminal

Why Semi-Gradient TD

Note that the above algorithm is called \textbf{semi-gradient}, because it does not backpropagate through $\hat{\varphi}(S_{t+1}; \mathbf{w})$:

$$\mathbf{w} \leftarrow \mathbf{w} + \alpha \left( R_{t+1} + \neg \text{done} \right) \cdot \gamma \hat{\varphi}(S_{t+1}; \mathbf{w}) - \hat{\varphi}(S_{t}; \mathbf{w}) \right) \nabla_{\mathbf{w}} \hat{\varphi}(S_{t}; \mathbf{w}) .$$

In other words, the above rule is in fact not an SGD update, because there does not exist a function $J(\mathbf{w})$, for which we would get the above update.

To sketch a proof, consider a linear $\hat{\varphi}(S_{t}; \mathbf{w}) = \sum_i x(S_t)_i w_i$ and assume such a $J(\mathbf{w})$ exists. Then

$$\frac{\partial}{\partial w_i} J(\mathbf{w}) = \left( R_{t+1} + \gamma \hat{\varphi}(S_{t+1}; \mathbf{w}) - \hat{\varphi}(S_{t}; \mathbf{w}) \right) x(S_t)_i .$$

Now considering second derivatives, we see they are not equal, which is a contradiction:

$$\frac{\partial}{\partial w_i} \frac{\partial}{\partial w_j} J(\mathbf{w}) = \left( \gamma x(S_{t+1})_i - x(S_t)_i \right) x(S_t)_j = \gamma x(S_{t+1})_i x(S_t)_j - x(S_t)_i x(S_t)_j$$

$$\frac{\partial}{\partial w_j} \frac{\partial}{\partial w_i} J(\mathbf{w}) = \left( \gamma x(S_{t+1})_j - x(S_t)_j \right) x(S_t)_i = \gamma x(S_{t+1})_j x(S_t)_i - x(S_t)_i x(S_t)_j$$
It can be proven (by using separate theory than for SGD) that the linear semi-gradient TD methods do converge.

However, they do not converge to the optimum of $\overline{V E}$. Instead, they converge to a different TD fixed point $w_{TD}$.

It can be proven that

$$
\overline{V E}(w_{TD}) \leq \frac{1}{1 - \gamma} \min_w \overline{V E}(w).
$$

However, when $\gamma$ is close to one, the multiplication factor in the above bound is quite large.
As before, we can utilize $n$-step TD methods.

**n-step semi-gradient TD for estimating $\hat{v} \approx v_\pi$**

Input: the policy $\pi$ to be evaluated
Input: a differentiable function $\hat{v}: S^+ \times \mathbb{R}^d \rightarrow \mathbb{R}$ such that $\hat{v}(\text{terminal}, \cdot) = 0$
Algorithm parameters: step size $\alpha > 0$, a positive integer $n$
Initialize value-function weights $w$ arbitrarily (e.g., $w = 0$)
All store and access operations ($S_t$ and $R_t$) can take their index mod $n + 1$

Loop for each episode:
  - Initialize and store $S_0 \neq \text{terminal}$
  - $T \leftarrow \infty$
  - Loop for $t = 0, 1, 2, \ldots$:
    - If $t < T$, then:
      - Take an action according to $\pi(\cdot|S_t)$
      - Observe and store the next reward as $R_{t+1}$ and the next state as $S_{t+1}$
      - If $S_{t+1}$ is terminal, then $T \leftarrow t + 1$
    - $\tau \leftarrow t - n + 1$ (\(\tau\) is the time whose state's estimate is being updated)
    - If $\tau \geq 0$:
      - $G \leftarrow \sum_{i=\tau+1}^{\min(\tau+n,T)} \gamma^{i-\tau-1} R_i$
      - If $\tau + n < T$, then: $G \leftarrow G + \gamma^n \hat{v}(S_{\tau+n}, w)$
      - $w \leftarrow w + \alpha [G - \hat{v}(S_\tau, w)] \nabla \hat{v}(S_\tau, w)$
  - Until $\tau = T - 1$

*Algorithm 9.5 of “Reinforcement Learning: An Introduction, Second Edition”.*
On the left, the results of one-step TD(0) algorithm is presented. The effect of increasing $n$ in an $n$-step variant is displayed on the right.
Until now, we talked only about policy evaluation. Naturally, we can extend it to a full Sarsa algorithm:

**Episodic Semi-gradient Sarsa for Estimating $\hat{q} \approx q^*$**

Input: a differentiable action-value function parameterization $\hat{q} : S \times A \times \mathbb{R}^d \rightarrow \mathbb{R}$

Algorithm parameters: step size $\alpha > 0$, small $\epsilon > 0$

Initialize action-value function weights $w \in \mathbb{R}^d$ arbitrarily (e.g., $w = 0$)

Loop for each episode:
- $S, A \leftarrow$ initial state and action of episode (e.g., $\epsilon$-greedy)

Loop for each step of episode:
- Take action $A$, observe $R, S'$
- If $S'$ is terminal:
  - $w \leftarrow w + \alpha [R - \hat{q}(S, A, w)] \nabla \hat{q}(S, A, w)$
  - Go to next episode
- Choose $A'$ as a function of $\hat{q}(S', \cdot, w)$ (e.g., $\epsilon$-greedy)

$$w \leftarrow w + \alpha [R + \gamma \hat{q}(S', A', w) - \hat{q}(S, A, w)] \nabla \hat{q}(S, A, w)$$

$S \leftarrow S'$

$A \leftarrow A'$

Modified from Algorithm 10.1 of "Reinforcement Learning: An Introduction, Second Edition".
Additionally, we can incorporate $n$-step returns:

Episodic semi-gradient $n$-step Sarsa for estimating $\hat{q} \approx q_s$ or $q_\pi$

Input: a differentiable action-value function parameterization $\hat{q} : S \times A \times \mathbb{R}^d \to \mathbb{R}$
Input: a policy $\pi$ (if estimating $q_\pi$)
Algorithm parameters: step size $\alpha > 0$, small $\epsilon > 0$, a positive integer $n$
Initialize action-value function weights $w \in \mathbb{R}^d$ arbitrarily (e.g., $w = 0$)
All store and access operations ($S_t$, $A_t$, and $R_t$) can take their index mod $n + 1$

Loop for each episode:
- Initialize and store $S_0 \neq$ terminal
- Select and store an action $A_0 \sim \pi(\cdot|S_0)$ or $\epsilon$-greedy wrt $\hat{q}(S_0, \cdot, w)$
- $T \leftarrow \infty$
- Loop for $t = 0, 1, 2, \ldots$:
  - If $t < T$, then:
    - Take action $A_t$
    - Observe and store the next reward as $R_{t+1}$ and the next state as $S_{t+1}$
    - If $S_{t+1}$ is terminal, then:
      - $T \leftarrow t + 1$
    - else:
      - Select and store $A_{t+1} \sim \pi(\cdot|S_{t+1})$ or $\epsilon$-greedy wrt $\hat{q}(S_{t+1}, \cdot, w)$
      - $\tau \leftarrow t - n + 1$  
        ($\tau$ is the time whose estimate is being updated)
      - If $\tau \geq 0$:
        - $G \leftarrow \sum_{i=\tau+1}^{\min(\tau+n,T)} \gamma^{i-\tau-1}R_i$
        - If $\tau + n < T$, then $G \leftarrow G + \gamma^n \hat{q}(S_{\tau+n}, A_{\tau+n}, w) \quad (G_{\tau+n})$
        - $w \leftarrow w + \alpha [G - \hat{q}(S_\tau, A_\tau, w)] \nabla \hat{q}(S_\tau, A_\tau, w)$
  - Until $\tau = T - 1$

Modified from Algorithm 10.2 of "Reinforcement Learning: An Introduction, Second Edition".
The performances are for semi-gradient Sarsa($\lambda$) algorithm (which we did not talked about yet) with tile coding of 8 overlapping tiles covering position and velocity, with offsets of $(1, 3)$. 

Figure 10.1 of "Reinforcement Learning: An Introduction, Second Edition".
Mountain Car Example

Figure 10.3 of "Reinforcement Learning: An Introduction, Second Edition".

Figure 10.4 of "Reinforcement Learning: An Introduction, Second Edition".
Off-policy Divergence With Function Approximation

Consider a deterministic transition between two states whose values are computed using the same weight:

\[ w \rightarrow 2w \]

Figure from Section 11.2 of "Reinforcement Learning: An Introduction, Second Edition".

- If initially \( w = 10 \), the TD error will be also 10 (or nearly 10 if \( \gamma < 1 \)).
- If for example \( \alpha = 0.1 \), \( w \) will be increased to 11 (by 10%).
- This process can continue indefinitely.

However, the problem arises only in off-policy setting, where we do not decrease value of the second state from further observation.
The previous idea can be implemented for instance by the following **Baird's counterexample**:

The rewards are zero everywhere, so the value function is also zero everywhere. We assume the initial values of weights are 1, except for $w_7 = 10$, and that the learning rate $\alpha = 0.01$.

\[ \pi(\text{solid}|\cdot) = 1 \]
\[ b(\text{dashed}|\cdot) = \frac{6}{7} \]
\[ b(\text{solid}|\cdot) = \frac{1}{7} \]
\[ \gamma = 0.99 \]
For off-policy semi-gradient Sarsa, or even for off-policy dynamic-programming update (where we compute expectation over all following states and actions), the weights diverge to $+\infty$. Using on-policy distribution converges fine.

\[
\mathbf{w} \leftarrow \mathbf{w} + \frac{\alpha}{|S|} \sum_s \left( \mathbb{E}_\pi \left[ R_{t+1} + \gamma \hat{v}(S_{t+1}; \mathbf{w}) \big| S_t = s \right] - \hat{v}(s; \mathbf{w}) \right) \nabla \hat{v}(s; \mathbf{w})
\]
The divergence can happen when all following elements are combined:

- functional approximation;
- bootstrapping;
- off-policy training.

In the Sutton's and Barto's book, these are called the **deadly triad**.
Deep Q Networks


Off-policy Q-learning algorithm with a convolutional neural network function approximation of action-value function.

Training can be extremely brittle (and can even diverge as shown earlier).
Deep Q Network

Figure 1 of "Human-level control through deep reinforcement learning" by Volodymyr Mnih et al.

NPFL122, Lecture 4

Function Approximation  Tile Coding  Semi-Gradient TD  Off-policy Divergence  DQN
• Preprocessing: 210 × 160 128-color images are converted to grayscale and then resized to 84 × 84.
• Frame skipping technique is used, i.e., only every 4\textsuperscript{th} frame (out of 60 per second) is considered, and the selected action is repeated on the other frames.
• Input to the network are last 4 frames (considering only the frames kept by frame skipping), i.e., an image with 4 channels.
• The network is fairly standard, performing
  ○ 32 filters of size 8 × 8 with stride 4 and ReLU,
  ○ 64 filters of size 4 × 4 with stride 2 and ReLU,
  ○ 64 filters of size 3 × 3 with stride 1 and ReLU,
  ○ fully connected layer with 512 units and ReLU,
  ○ output layer with 18 output units (one for each action)
Deep Q Networks

- Network is trained with RMSProp to minimize the following loss:

\[ \mathcal{L} \overset{\text{def}}{=} \mathbb{E}_{(s,a,r,s') \sim \text{data}} \left[ (r + [-\text{done}] \cdot \gamma \max_{a'} Q(s', a'; \bar{\theta}) - Q(s, a; \theta))^2 \right]. \]

- An \( \epsilon \)-greedy behavior policy is utilized (starts at \( \epsilon = 1 \) and gradually decreases to 0.1).

Important improvements:

- **experience replay**: the generated episodes are stored in a buffer as \((s, a, r, s')\) quadruples, and for training a transition is sampled uniformly (off-policy training);
- separate **target network** \( \bar{\theta} \): to prevent instabilities, a separate target network is used to estimate one-step returns. The weights are not trained, but copied from the trained network after a fixed number of gradient updates;
- reward clipping: because rewards have wildly different scale in different games, all positive rewards are replaced by +1 and negative by −1; life loss is used as an end of episode.
  - furthermore, \((r + [-\text{done}] \cdot \gamma \max_{a'} Q(s', a'; \bar{\theta}) - Q(s, a; \theta))^2\) is also clipped to \([-1, 1]\) (i.e., a smooth \( L_1 \) loss or Huber loss).
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 $a_t = \text{argmax}_a Q(\phi(s_t), a; \theta)$
    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

Algorithm 1 of "Human-level control through deep reinforcement learning" by Volodymyr Mnih et al.
Deep Q Network

Figure 3 of "Human-level control through deep reinforcement learning" by Volodymyr Mnih et al.
Deep Q Network

Extended Data Figure 2a of “Human-level control through deep reinforcement learning” by Volodymyr Mnih et al.
Extended Data Figure 2b of "Human-level control through deep reinforcement learning" by Volodymyr Mnih et al.
## Deep Q Networks Hyperparameters

<table>
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<tr>
<th>Hyperparameter</th>
<th>Value</th>
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<tr>
<td>replay buffer size</td>
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<td>no-op max</td>
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