Evan Hubinger and Jonah Rubin
CS 152
DQL Math

Let

- $t \in \mathbb{N}$ be the current time step,
- $\boldsymbol{x}_t \in \mathbb{R}^d$ be the input at time t,
- $a_t \in A$ be the action taken at time t based on input $\boldsymbol{x}_t$, and
- $r_t \in \mathbb{R}$ be the reward received at time t based on action a_t.

Once x_{t+1} is observed, we'll define

$$s_{t+1} = \begin{bmatrix} \boldsymbol{x}_1 & a_1 & \boldsymbol{x}_2 & a_2 & \dots & \boldsymbol{x}_{t-1} & a_{t-1} & \boldsymbol{x}_t & a_t & x_{t+1} \end{bmatrix}$$

then, our goal is to use $\boldsymbol{s}_{t+1}$ to predict the best a_{t+1}.

First, we'll define what we mean by best. Let $T \in \mathbb{N}$ be the total number of time steps, and γ some discount rate on future rewards. Then, we'll define the future discounted return as

$$R_t = \sum_{t'=t}^{T} \gamma^{t'-t} r_{t'}$$

which is what we'll be trying to optimize for. To do this, we want to find a function $Q(\boldsymbol{s}_t, a_t)$ which will tell us the future discounted return for taking action a_t given history $\boldsymbol{s}_t$. Specifically, we'll define the optimal Q^*, which we'll be trying to approximate, as

$$Q^*(\boldsymbol{s}_t, a_t) = \max_\pi \mathbb{E}_{\boldsymbol{s}_t, a_t, \pi} \left[R_t\right]$$

where $\pi : \{s \,|\, \forall s\} \to A$ is some policy for selecting actions based on states. Then, given Q^*, we can find the optimal action a_t^* as

$$a_t^* = \text{argmax}_{a'} \left(r_t + \gamma Q^*(\boldsymbol{s}_t, a')\right)$$

therefore, if we can find an approximation for Q^*, we can also find an approximation for a_t^*, which is our actual goal. To do this, we want to find an iterative update rule for Q. Thus, we can rewrite the above formula for Q^* recursively as

$$Q^*(\boldsymbol{s}_t, a_t) = \mathbb{E}_{\boldsymbol{x}_{t+1}}\left[r_t + \gamma \max_{a'} Q^*(\boldsymbol{s}_{t+1}, a')\right]$$

which gives us

$$Q_{i+1}(\boldsymbol{s}_t, a_t) = \mathbb{E}_{\boldsymbol{x}_{t+1}}\left[r_t + \gamma \max_{a'} Q_i(\boldsymbol{s}_{t+1}, a')\right]$$

which is the standard Q-learning update rule.

Next, we want to adopt this formulation to allow us to approximate Q with a neural network. Thus, for weights $\boldsymbol{\theta}$ and feature map ϕ, we'll let

$$Q(\phi(\boldsymbol{s}_t), a_{t+1} \,|\, \boldsymbol{\theta})$$

be our new Q. Then, we'll define the target value at iteration i as

$$y_i(\boldsymbol{s}_t, a_t) = \mathbb{E}_{\boldsymbol{x}_{t+1}}\left[r_t + \gamma \max_{a'} Q(\phi(\boldsymbol{s}_{t+1}), a' \,|\, \boldsymbol{\theta}_i)\right]$$

which gives us the squared-loss loss function

$$L_i(\boldsymbol{\theta}_i) = \frac{1}{2}\mathbb{E}_{\boldsymbol{s}_t, a_t}\left[(y_i(\boldsymbol{s}_t, a_t) - Q(\phi(\boldsymbol{s}_t), a_t \,|\, \boldsymbol{\theta}_i))^2\right]$$

which says that, for all states and actions, we want Q to be as close to the estimated future discounted reward as possible. Interestingly, note that we are using Q both as our predicted value and in constructing our target.

Finally, using our loss function, we can construct an update rule for $\boldsymbol{\theta}$ which will actually let us train our deep Q-learning neural net. Taking the gradient of L_i, we get

$$\nabla_{\boldsymbol{\theta}_i} L_i(\boldsymbol{\theta}_i) =$$
$$-\mathbb{E}_{\boldsymbol{s}_t, a_t, \boldsymbol{x}_{t+1}}\left[\left(r_t + \gamma \max_{a'} Q(\phi(\boldsymbol{s}_{t+1}), a' \,|\, \boldsymbol{\theta}_i) - Q(\phi(\boldsymbol{s}_t), a_t \,|\, \boldsymbol{\theta}_i)\right) \nabla_{\boldsymbol{\theta}_i} Q(\phi(\boldsymbol{s}_t), a_t \,|\, \boldsymbol{\theta}_i)\right]$$

which gives the gradient descent update rule for $\boldsymbol{\theta}_i$

$$\boldsymbol{\theta}_{i+1} = \boldsymbol{\theta}_i - \eta \nabla_{\boldsymbol{\theta}_i} L_i(\boldsymbol{\theta}_i)$$

where η is the learning rate, which we can use to train our network.