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# Deep Q-Learning with Recurrent Neural Networks

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## Abstract

Deep reinforcement learning models have proven to be successful at learning control policies image inputs. They have, however, struggled with learning policies that require longer term information. Recurrent neural network architectures have been used in tasks dealing with longer term dependencies between data points. We investigate these architectures to overcome the difficulties arising from learning policies with long term dependencies.

## 1 Introduction

Recent advances in reinforcement Learning have led to human-level or greater performance on a wide variety of games (e.g. Atari 2600 Games). However, training these networks can take a long time, and the techniques presented in the state of the art [0] perform poorly on several games that require long term planning.

Deep Q-networks are limited in that they learn a mapping from a single previous state which consists of a small number of game screens. In practice, DQN is trained using an input consisting of the last four game screens. Thus, DQN performs poorly at games that require the agent to remember information more than four screens ago. This is evident from the types of games DQN performs poorly at, near or below human-level, in Figure 1.

We explore the concept of a deep recurrent Q-network (DRQN), a combination of a recurrent neural network (RNN) [6] and a deep Q-network (DQN) similar to [5]. The idea being that the RNN will be able to retain information from states further back in time and incorporate that into predicting better Q values and thus performing better on games that require long term planning.

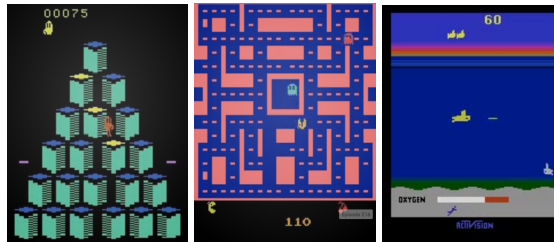


Figure 1: Q\*bert, Ms. Pac-Man and Montezuma's Revenge

In addition to vanilla RNN architectures we also examine augmented RNN architectures such as attention RNNs. Recent achievements of attention RNNs in translation tasks [2, 3] have shown promise. The advantage of using attention is that it enables DRQN to focus on particular previous states it deems important for predicting the action in the current state. We investigate augmenting DRQN with attention and evaluate its usefulness.

## 2 Deep Q-Learning

We examine agents playing Atari games. In our environment the agents interact with an Atari emulator. At time  $t$  they receive an observation  $x_t \in \mathbb{R}^D$  which is a vector of pixels from the current game screen. The agent then takes an action,  $a_t \in \mathcal{A} = \{1, \dots, K\}$  and receives a reward  $r_t$  which is the change in the game score.

The objective of the agent is to take actions that maximize the future discounted rewards. We can calculate the future rewards with  $R_t = \sum_{t'=1}^T \gamma^{t'-1} r_{t'}$  where  $T$  is the end of the game and  $\gamma$  is our discount factor. One way to achieve this objective is to find the optimal action-value function:

$$Q^*(s, a) = \max_{\pi} \mathbb{E}[r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \dots | s_t = s, a_t = a, \pi]$$

which is the expected value of the future discounted rewards under the policy  $\pi = P(a|s)$ , or the probability of taking an action given the agent is in a certain state. Unfortunately this method can be very difficult to calculate it so we approximate it with another function  $Q(s, a; \theta) \approx Q^*(s, a)$ . We examine several different types of deep neural network architectures for our function approximator which are called Q-networks.

Training this function can be unstable and will sometimes diverge. The following following loss function is used to help reduce some of these issues [0]:

$$L_i(\theta_i) = \mathbb{E}_{(s, a, r, s') \sim U(D)} \left[ \left( r + \gamma \max_{a'} Q(s', a'; \theta_i^-) - Q(s, a; \theta_i) \right)^2 \right] \quad (1)$$

Where experiences are defined as  $e_t = (s_t, a_t, r_t, s_{t+1})$  and  $D_t = \{e_1, \dots, e_t\}$ . Experiences are drawn uniformly from our pool of stored experiences,  $e_t \sim U(D)$ .

## 3 Deep Recurrent Q-Learning

We propose three architectures for the Deep Recurrent Q-Network (DRQN). The first is a very basic extension of DQN. The architecture of DRQN augments DQN's fully connected layer with a LSTM. We accomplish this by looking at the last  $L$  states,  $\{s_{t-(L-1)}, \dots, s_t\}$  and feed these into a convolutional neural network (CNN) to get intermediate outputs  $\text{CNN}(s_{t-i}) = x_{t-i}$ . These are then fed into a RNN (we use an LSTM for this but it can be any RNN),  $\text{RNN}(x_{t-i}, h_{t-i-1}) = h_{t-i}$ , and the final output  $h_t$  is used to predict the  $Q$  value which is now a function of  $Q(\{s_{t-(L-1)}, \dots, s_t\}, a_t)$ .

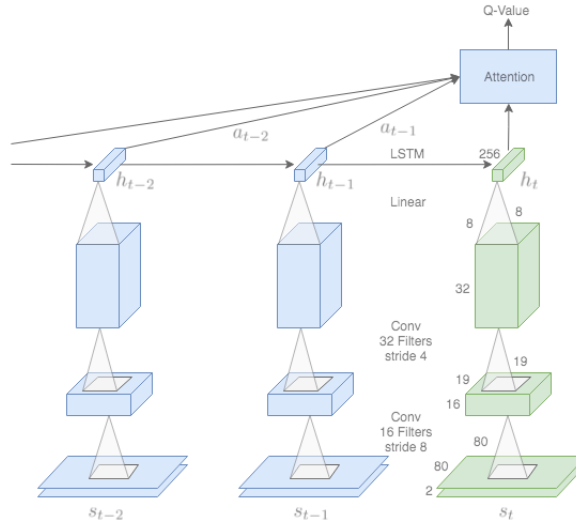


Figure 2: Architecture of the Attention DRQN

The second architecture we used was a version of an attention RNN, depicted in Figure 2, we are calling linear attention. For the linear attention RNN we take the  $L$  hidden states outputted by

the RNN,  $\{h_{t-(L-1)}, \dots, h_t\}$  and calculate an inner product with  $v_a$ ,  $\{v_a^T h_{t-(L-1)}, \dots, v_a^T h_t\}$ . This allows the model to focus more on nearby hidden states or further away states depending on what values of  $v_a$  are learned. We then take a softmax over these values,  $a_{t-i} = \text{softmax}(v_a^T h_{t-i})$ . We use this softmax to take a weighted sum over the hidden states to get a context vector,  $c_t = \sum_{i=0}^{L-1} a_{t-i} h_{t-i}$ . This context vector is then used to predict the  $Q$  value.

The third architecture we used is global attention, similar to the global attention used in [3]. A diagram of this type of attention can be seen in Figure 2. We treat the current state,  $s_t$  as the "decoder" input and the previous  $L - 2$  states as the "encoder" inputs. We compute the following scores,  $\{h_{t-(L-1)}^T h_t, \dots, h_{t-1}^T h_t\}$ . We then take a softmax over these values,  $a_{t-i} = \text{softmax}(h_{t-i}^T h_t)$ . The context vector is computed as a weighted sum over the previous hidden states,  $c_t = \sum_{i=1}^{L-1} a_{t-i} h_{t-i}$ . Finally the context vector is used to compute  $\tilde{h} = \tanh(W_a[h_t; c_t] + b_a)$  which is then used to predict the  $Q$  value. This type of attention allows the model to focus on previous states depending on the current state  $h_t$  as opposed to a fixed vector such as  $v_a$ .

Learning sequences of observations creates some difficulty when sampling experiences and using the loss function defined in (1). We propose a simple solution where we sample  $e_t \sim U(D)$  and then take the previous  $L$  states,  $\{s_{t-(L+1)}, \dots, s_t\}$  and zero out states from previous games. For example if  $s_{t-i}$  was the end of the previous game then we would have states  $\{0, \dots, 0, s_{t-(i+1)}, \dots, s_t\}$  and similarly for the next state  $\{0, \dots, 0, s_{t-(i+2)}, \dots, s_{t+1}\}$ .

## 4 Experiments

For our experiments we mainly focused on the game Q\*bert. We chose Q\*bert because it was a challenging game for DQN which achieved scores only slightly above human-level [0] but it was not so challenging that DQN could not make any progress, such as Montezuma's Revenge [0].

For input the DRQN takes a specified number of screens per state. The screen images are grayscale and resized to  $80 \times 80$ . The first hidden layer convolves 16,  $19 \times 19$  filters with stride 8 across the input image and applies a rectified linear unit. The second hidden layer convolves 32,  $8 \times 8$  filters with stride 4, again followed by a rectified linear unit. Convolutional outputs are fed to an LSTM with 256 hidden units per layer. Finally, a fully connected linear layer outputs a  $Q$ -value for each possible action.

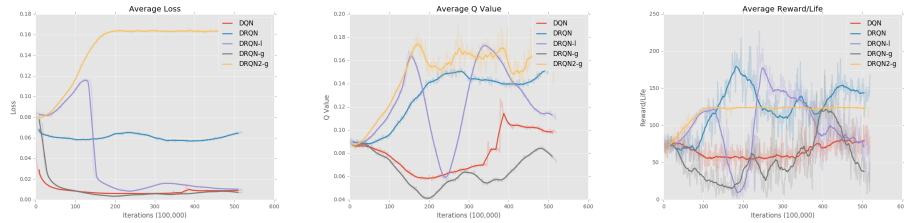


Figure 3: Graphs for Q\*bert Over Iterations

For Figure 3 we trained 4 different models for about 5 million iterations on Q\*bert which took about 6 days to complete. All the models use the same convolutional neural network described above for processing the images. DQN uses 4 game screens per state. All the DRQN models use  $L = 16$  and 2 screens per state. DRQN is a basic recurrent model with no attention mechanism. DRQN-l is the recurrent model with linear attention. DRQN-g is the recurrent model with global attention and DRQN2-g is the same as DRQN-g except with a 2 layer LSTM.

As you can see from Figure 3 the graphs for the DRQN models are very noisy. The regular DRQN performed the best in terms of average points per life but also had the most difficult time reducing the loss. DRQN-l had the noisiest graphs. It performed close to the highest and lowest value at some point on every statistic. DRQN-g's performance was disappointing. It had the easiest time

minimizing the loss but struggled to gain momentum on average reward per life. Interestingly, when we added another layer, while it had a harder time minimizing the loss, the average score was much more consistent and seemed to converge.

	Best Score for Q*bert
<b>DQN</b>	700
<b>DRQN</b>	<b>850</b>
<b>DRQN-l</b>	700
<b>DRQN-g</b>	550

Figure 4: Best Scores for Q\*bert

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