CS230: Lecture 9
Deep Reinforcement Learning
Kian Katanforoosh
I. Motivation
II. Recycling is good: an introduction to RL
III. Deep Q-Learning
IV. Application of Deep Q-Learning: Breakout (Atari)
V. Tips to train Deep Q-Network
VI. Advanced topics
1. Motivation

Human Level Control through Deep Reinforcement Learning

AlphaGo

Mastering the Game of Go without Human Knowledge
DeepMind, 5 New Street Square, London EC4A 3TW.
*These authors contributed equally to this work.

A long-standing goal of artificial intelligence is an algorithm that learns, tabula rasa, superhuman proficiency in challenging domains. Recently, AlphaGo became the first program to defeat a world champion in the game of Go. The tree search in AlphaGo evaluated positions and selected moves using deep neural networks. These neural networks were trained by supervised learning from human expert move, and by reinforcement learning from self-play. Here, we introduce an algorithm based solely on reinforcement learning, without human data, guidance, or domain knowledge beyond game rules. AlphaGo becomes its own teacher: a neural network is trained to predict AlphaGo’s own move selections and also the winner of AlphaGo’s games. This neural network improves the strength of tree search, resulting in higher quality move selection and stronger self-play in the next iteration. Starting tabula rasa, our new program AlphaGo Zero achieved superhuman performance, winning 100-0 against the previously published, champion-defeating AlphaGo.

AlphaStar

[Silver, Schrittwieser, Simonyan et al. (2017): Mastering the game of Go without human knowledge]
[Vinyals et al. (2019): Grandmaster level in StarCraft II using multi-agent reinforcement learning]
[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
I. Motivation

How would you solve Go with classic supervised learning?

Why RL?
- Delayed labels
- Making sequences of decisions

What is RL?
- Automatically learn to make good sequences of decision
- Teaching by experience vs. Teaching by example.

Issues:
- Ground truth probably wrongly defined.
- Too many states in this Game.
- We will likely not generalize.

Examples of RL applications

Games

Robotics

Advertisement

Source: https://deepmind.com/blog/alphago-zero-learning-scratch/
I. Motivation

Transition: $s_t \rightarrow a_t \rightarrow (o_t, r_t) \rightarrow s_{t+1}$
I. Motivation

II. Recycling is good: an introduction to RL

III. Deep Q-Networks

IV. Application of Deep Q-Network: Breakout (Atari)

V. Tips to train Deep Q-Network

VI. Advanced topics
**Problem statement**

**Goal**: maximize the return (rewards)

**Number of states**: 5

**Types of states**:
- **initial**
- **normal**
- **terminal**

**Agent’s Possible actions**:

*Define reward “r” in every state*

<table>
<thead>
<tr>
<th>State 1</th>
<th>State 2 (initial)</th>
<th>State 3</th>
<th>State 4</th>
<th>State 5</th>
</tr>
</thead>
</table>

+2 0 0 +1 +10

**Best strategy to follow if** \( \gamma = 1 \)

**Additional rule**: garbage collector coming in 3min, it takes 1min to move between states

**How to define the long-term return?**

Discounted return:

\[
R = \sum_{t=0}^{\infty} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + \ldots
\]
II. Recycling is good: an introduction to RL

Problem statement

What do we want to learn?

Define reward “r” in every state

Assuming $\gamma = 0.9$

Discounted return $R = \sum_{t=0}^{\infty} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + ...$

Q-table

How?
**II. Recycling is good: an introduction to RL**

**Problem statement**

- Define reward “r” in every state

<table>
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<tbody>
<tr>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
<td>S5</td>
</tr>
<tr>
<td>+2</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>+10</td>
</tr>
</tbody>
</table>

Assuming $\gamma = 0.9$

**Discounted return**

$$ R = \sum_{t=0}^{\infty} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + ... $$

**What do we want to learn?**

how good is it to take action 1 in state 2

**Q-table**

$$ Q = \begin{pmatrix}
Q_{11} & Q_{12} \\
Q_{21} & Q_{22} \\
Q_{31} & Q_{32} \\
Q_{41} & Q_{42} \\
Q_{51} & Q_{52}
\end{pmatrix} $$

**How?**

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II. Recycling is good: an introduction to RL

Problem statement

Define reward “r” in every state

+2 0 0 +1 +10

S1 S2 S3 S4 S5

Assuming \( \gamma = 0.9 \)

Discounted return

\[ R = \sum_{t=0} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + \ldots \]

What do we want to learn?

how good is it to take action 1 in state 2

Q-table

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How?

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II. Recycling is good: an introduction to RL

Problem statement

Define reward “r” in every state

What do we want to learn?

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Q-table

How?

Assuming $\gamma = 0.9$

Discounted return $R = \sum_{t=0}^{\infty} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + ...$
**II. Recycling is good: an introduction to RL**

**Problem statement**

```
       S1      S2      S3      S4      S5
State 1:  START  S2 (initial)  State 3  State 4  State 5
```

**Define reward “r” in every state**

<table>
<thead>
<tr>
<th>State</th>
<th>Reward</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>+2</td>
</tr>
<tr>
<td>S2</td>
<td>0</td>
</tr>
<tr>
<td>S3</td>
<td>0</td>
</tr>
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<td>+10</td>
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Assuming $\gamma = 0.9$

**Discounted return**

$R = \sum_{t=0}^{\infty} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + ...$

**What do we want to learn?**

How good is it to take action 1 in state 2

**Q-table**

$Q = \begin{pmatrix}
Q_{11} & Q_{12} \\
Q_{21} & Q_{22} \\
Q_{31} & Q_{32} \\
Q_{41} & Q_{42} \\
Q_{51} & Q_{52}
\end{pmatrix}$

**How?**

- $R = 8.1 + 9 + 10 = 27.1$
- $R = 9 + 10 = 19$
- $R = 10 + 10 = 20$
- $R = 8.1 + 9 + 10 = 27.1$
- $R = 9 + 10 = 19$
- $R = 10 + 10 = 20$

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II. Recycling is good: an introduction to RL

Problem statement

Define reward “r” in every state

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<td>+2</td>
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Assuming $\gamma = 0.9$

Discounted return $R = \sum_{t=0}^{\infty} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + ...$

What do we want to learn?

how good is it to take action 1 in state 2

$Q$-table

How?

Assuming $\gamma = 0.9$, how good is it to take action 1 in state 2.

Discounted return $R = \sum_{t=0}^{\infty} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + ...$
II. Recycling is good: an introduction to RL

Problem statement

Define reward “r” in every state

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Assuming $\gamma = 0.9$

Discounted return $R = \sum_{t=0}^{\infty} \gamma^t r_t = r_0 + \gamma r_1 + \gamma^2 r_2 + ...$

What do we want to learn?

How good is it to take action 1 in state 2

$Q$-table

Assuming $\gamma = 0.9$

How?

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II. Recycling is good: an introduction to RL

Problem statement

- Define reward “r” in every state
- What do we want to learn?
  - how good is it to take action 1 in state 2

Q-table

Bellman equation (optimality equation)

\[ Q^*(s, a) = r + \gamma \max_{a'}(Q^*(s', a')) \]

Policy

\[ \pi(s) = \arg \max_a(Q^*(s, a)) \]

Best strategy to follow if $\gamma = 0.9$

- Function telling us our best strategy
- When state and action spaces are too large, this method has huge memory cost
What we’ve learned so far:

- **Vocabulary**: environment, agent, state, action, reward, total return, discount factor.

- **Q-table**: matrix of entries representing “how good is it to take action a in state s”

- **Policy**: function telling us what’s the best strategy to adopt

- **Bellman equation** satisfied by the optimal Q-table
I. Motivation

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III. Deep Q-Learning

Main idea: find a Q-function to replace the Q-table

Problem statement

Neural Network

\[
\begin{bmatrix}
0 & 0 \\
2 & 9 \\
8.1 & 10 \\
9 & 10 \\
0 & 0
\end{bmatrix}
\]

\[
\left[
\begin{array}{c}
0 \\
1 \\
0 \\
0
\end{array}
\right]
\]

\[
Q(s, \rightarrow)
\]

\[
Q(s, \leftarrow)
\]

How to compute the loss?
III. Deep Q-Learning

\[ Q^*(s,a) = r + \gamma \max_{a'} (Q^*(s',a')) \]

Loss function

\[ L = (y - Q(s,\leftarrow))^2 \]

Target value

Case: \[ Q(s,\leftarrow) > Q(s,\rightarrow) \]

\[ y = r_{\leftarrow} + \gamma \max_{a'} (Q(s_{\text{next}}^{\leftarrow},a')) \]

Immediate reward for taking action \( \leftarrow \) in state \( s \)

Discounted maximum future reward when you are in state \( s_{\text{next}}^{\leftarrow} \)

Hold fixed for backprop

Case: \[ Q(s,\leftarrow) < Q(s,\rightarrow) \]

\[ y = r_{\rightarrow} + \gamma \max_{a'} (Q(s_{\text{next}}^{\rightarrow},a')) \]

Immediate Reward for taking action \( \rightarrow \) in state \( s \)

Discounted maximum future reward when you are in state \( s_{\text{next}}^{\rightarrow} \)

Hold fixed for backprop

[Francisco S. Melo: Convergence of Q-learning: a simple proof]
III. Deep Q-Learning

\[
s = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}
\]

\[
\begin{align*}
\begin{array}{c}
 a_1^{[1]} \\
a_2^{[1]} \\
a_3^{[1]} \\
a_4^{[1]} \\
a_1^{[2]} \\
a_2^{[2]} \\
a_3^{[2]} \\
a_4^{[2]} \\
a_1^{[3]} \\
a_2^{[3]} \\
a_3^{[3]} \\
\end{array}
\rightarrow Q(s, \leftarrow) \\
\rightarrow Q(s, \rightarrow)
\end{align*}
\]

Loss function (regression)

\[
L = (y - Q(s, \rightarrow))^2
\]

Target value

Case: \( Q(s, \leftarrow) > Q(s, \rightarrow) \)

\[
y = r_\leftarrow + \gamma \max_{a'} (Q(s_{\leftarrow}^{next}, a'))
\]

Case: \( Q(s, \leftarrow) < Q(s, \rightarrow) \)

\[
y = r_\rightarrow + \gamma \max_{a'} (Q(s_{\rightarrow}^{next}, a'))
\]

Backpropagation

Compute \( \frac{\partial L}{\partial W} \) and update W using stochastic gradient descent

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**Recap’**

\[ y = r + \gamma \max_{a'} Q(s^{next}, a') \]

**DQN Implementation:**

- Initialize your Q-network parameters
- Loop over episodes:
  - Start from initial state s
  - Loop over time-steps:
    - Forward propagate s in the Q-network
    - Execute action a (that has the maximum Q(s,a) output of Q-network)
    - Observe reward r and next state s’
    - Compute targets y by forward propagating state s’ in the Q-network, then compute loss.
    - Update parameters with gradient descent
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IV. Deep Q-Learning application: Breakout (Atari)

Goal: play breakout, i.e. destroy all the bricks.

Demo

input of Q-network

Output of Q-network

\[
\begin{pmatrix}
Q(s, \leftarrow) \\
Q(s, \rightarrow) \\
Q(s, \rightarrow)
\end{pmatrix}
\]

Would that work?

[Video credits to Two minute papers: Google DeepMind's Deep Q-learning playing Atari Breakout https://www.youtube.com/watch?v=V1eYniJ0Rnk]

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
Goal: play breakout, i.e. destroy all the bricks.

IV. Deep Q-Learning application: Breakout (Atari)

What is done in preprocessing?
- Convert to grayscale
- Reduce dimensions (h,w)
- History (4 frames)

[Video credits to Two minute papers: Google DeepMind’s Deep Q-learning playing Atari Breakout](https://www.youtube.com/watch?v=V1eYniJ0Rnk)

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
IV. Deep Q-Learning application: Breakout (Atari)

**input of Q-network**

\[
\phi(s) = \begin{bmatrix} 0 \ 0 \ 0 \ 1 \end{bmatrix}
\]

**Deep Q-network architecture?**

\[
\phi(s) \rightarrow \text{CONV} \rightarrow \text{ReLU} \rightarrow \text{CONV} \rightarrow \text{ReLU} \rightarrow \text{CONV} \rightarrow \text{ReLU} \rightarrow \text{FC (RELU)} \rightarrow \text{FC (LINEAR)} \rightarrow \begin{bmatrix} Q(s,\leftarrow) \\ Q(s,\rightarrow) \\ Q(s,\neg) \end{bmatrix}
\]

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
Recap’ (+ preprocessing + terminal state)

**DQN Implementation:**

- Initialize your Q-network parameters
- Loop over episodes:
  - Start from initial state $s$
  - Loop over time-steps:
    - Forward propagate $s$ in the Q-network
    - Execute action $a$ (that has the maximum $Q(s,a)$ output of Q-network)
    - Observe reward $r$ and next state $s'$
    - Use $s'$ to create $\phi(s')$
    - Compute targets $y$ by forward propagating state $s'$ in the Q-network, then compute loss.
    - Update parameters with gradient descent

**Some training challenges:**
- Keep track of terminal step
- Experience replay
- Epsilon greedy action choice (Exploration / Exploitation tradeoff)

[Shah, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
Recap’ (+ preprocessing + terminal state)

**DQN Implementation:**
- Initialize your Q-network parameters
- Loop over episodes:
  - Start from initial state $s$
  - Loop over time-steps: $s$
    - Forward propagate $s$ in the Q-network
    - Execute action $a$ (that has the maximum $Q(s,a)$ output of Q-network)
    - Observe reward $r$ and next state $s'$
  - Use $s'$ to create $s''$
    - Compute targets $y$ by forward propagating state $s$ in the Q-network, then compute loss.
    - Update parameters with gradient descent

Some training challenges:
- Keep track of terminal step
- Experience replay
- Epsilon greedy action choice
  (Exploration / Exploitation tradeoff)

[<Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning>]
Recap’ (+ preprocessing + terminal state)

**DQN Implementation:**
- Initialize your Q-network parameters
- Loop over episodes:
  - Start from initial state
  - Create a boolean to detect terminal states: \( \text{terminal} = \text{False} \)
  - Loop over time-steps:
    - Forward propagate \( s \) in the Q-network
    - Execute action \( a \) (that has the maximum \( Q(s,a) \) output of Q-network)
    - Observe reward \( r \) and next state \( s' \)
    - Use \( s' \) to create \( \phi(s') \)
    - **Check if \( s' \) is a terminal state.** Compute targets \( y \) by forward propagating state \( s' \) in the Q-network, then compute loss.
    - Update parameters with gradient descent

**Some training challenges:**
- Keep track of terminal step
- Experience replay
- Epsilon greedy action choice
  (Exploration / Exploitation tradeoff)

\[
\begin{align*}
\text{if} & \quad \text{terminal} = \text{False} \quad : \\
& \quad y = r + \gamma \max_{a'} (Q(s',a')) \\
\text{if} & \quad \text{terminal} = \text{True} \quad : \\
& \quad y = r \quad \text{(break)}
\end{align*}
\]

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
Experience replay

Current method is to start from initial state $s$ and follow:

1. $E_1: \phi(s) \rightarrow a \rightarrow r \rightarrow \phi(s')$
2. $E_2: \phi(s') \rightarrow a' \rightarrow r' \rightarrow \phi(s'')$
3. $E_3: \phi(s'') \rightarrow a'' \rightarrow r'' \rightarrow \phi(s''')$

... 

Training: $E_1 \rightarrow E_2 \rightarrow E_3$

Experience Replay

- $E_1$
- $E_2$
- $E_3$
- ...

Can be used with mini batch gradient descent

Advantages of experience replay?

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
**DQN Implementation:**

- Initialize your Q-network parameters
- **Initialize replay memory D**
- Loop over episodes:
  - Start from initial state $\phi(s)$
  - Create a boolean to detect terminal states: terminal = False
  - Loop over time-steps:
    - Forward propagate $\phi(s)$ in the Q-network
    - Execute action $a$ (that has the maximum $Q(\phi(s), a)$ output of Q-network)
    - Observe reward $r$ and next state $s'$
    - Use $s'$ to create $\phi(s')$
    - **Add experience $(\phi(s), a, r, \phi(s'))$ to replay memory (D)**

**Sample random mini-batch of transitions from D**

- Check if $s'$ is a terminal state. Compute targets $y$ by forward propagating state $\phi(s')$ in the Q-network, then compute loss.
- Update parameters with gradient descent

**Some training challenges:**

- Keep track of terminal step
- Experience replay
- Epsilon greedy action choice (Exploration / Exploitation tradeoff)

---

The transition resulting from this is added to D, and will not necessarily be used in this iteration’s update!
Exploration vs. Exploitation

Just after initializing the Q-network, we get:

- \( Q(S1, a_1) = 0.5 \)
- \( Q(S1, a_2) = 0.4 \)
- \( Q(S1, a_3) = 0.3 \)
Exploration vs. Exploitation

Just after initializing the Q-network, we get:

- $Q(S_1, a_1) = 0.5$
- $Q(S_1, a_2) = 0.4$
- $Q(S_1, a_3) = 0.3$
Exploration vs. Exploitation

Just after initializing the Q-network, we get:

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Exploration vs. Exploitation

Just after initializing the Q-network, we get:

\[
Q(S_1, a_1) = 0.5 \\
Q(S_1, a_2) = 0.4 \\
Q(S_1, a_3) = 0.3
\]

Will never be visited, because \( Q(S_1, a_3) < Q(S_1, a_2) \)
DQN Implementation:

- Initialize your Q-network parameters
- Initialize replay memory $D$

- Loop over episodes:
  - Start from initial state $\phi(s)$
  - Create a boolean to detect terminal states: $\text{terminal} = \text{False}$

- Loop over time-steps:
  - With probability $\epsilon$, take random action $a$.
  - Otherwise:
    - Forward propagate $\phi(s)$ in the Q-network
    - Execute action $a$ (that has the maximum $Q(\phi(s),a)$ output of Q-network).

  - Observe reward $r$ and next state $s'$
  - Use $s'$ to create $\phi(s')$
  - Add experience $(\phi(s),a,r,\phi(s'))$ to replay memory ($D$)
  - Sample random mini-batch of transitions from $D$

  - Check if $s'$ is a terminal state. Compute targets $y$ by forward propagating state $\phi(s')$ in the Q-network, then compute loss.

  - Update parameters with gradient descent

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
Overall recap’

**DQN Implementation:**

- Initialize your Q-network parameters
- **Initialize replay memory** $D$
- Loop over episodes:
  - Start from initial state $\phi(s)$
  - Create a boolean to detect terminal states: $\text{terminal} = \text{False}$
  - Loop over time-steps:
    - With probability epsilon, take random action $a$.
    - Otherwise:
      - Forward propagate $\phi(s)$ in the Q-network
      - Execute action $a$ (that has the maximum $Q(\phi(s), a)$ output of Q-network).
    - Observe rewards $r$ and next state $s'$
    - **Use $s'$ to create** $\phi(s')$
    - **Add experience** $(\phi(s), a, r, \phi(s'))$ **to replay memory** $(D)$
    - Sample random mini-batch of transitions from $D$
    - Check if $s'$ is a terminal state. Compute targets $y$ by forward propagating state $\phi(s')$ in the Q-network, then compute loss.
    - Update parameters with gradient descent

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
Results

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
[Credits: DeepMind, DQN Breakout - https://www.youtube.com/watch?v=TMpFtjtdgg]
Other Atari games

Pong

SeaQuest

Space Invaders

[Chia-Hsuan Lee, Atari Seaquest Double DQN Agent - https://www.youtube.com/watch?v=NirMkC5uvWU]

[moooopan, Deep Q-Network Plays Atari 2600 Pong - https://www.youtube.com/watch?v=p88R2_3yWPA]

[DeepMind: DQN SPACE INVADERS - https://www.youtube.com/watch?v=W2CAghUiofY&t=2s]

[Mnih, Kavukcuoglu, Silver et al. (2015): Human Level Control through Deep Reinforcement Learning]
Difference between with and without human knowledge

Imitation learning

[Source: Bellemare et al. (2016): Unifying Count-Based Exploration and Intrinsic Motivation]

Ho et al. (2016): Generative Adversarial Imitation Learning]
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VI. Advanced topics
VI - Advanced topics

Policy Gradient Methods

PPO

TRPO

[Open Al Blog]

[TRPO]

[Schulman et al. (2017): Trust Region Policy Optimization]
[Schulman et al. (2017): Proximal Policy Optimization]

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VI - Advanced topics

Competitive self-play

[Bansal et al. (2017): Emergent Complexity via multi-agent competition]
[OpenAI Blog: Competitive self-play]
Open AI Five

[OpenAI Blog Five]

Deep Mind: Alpha Star

AlphaStar: Mastering the Real-Time Strategy Game StarCraft
VI - Advanced topics

Alpha Go

[DeepMind Blog]
[Silver, Schrittwieser, Simonyan et al. (2017): Mastering the game of Go without human knowledge]
This week is the project week:
- **Discussion section** on Friday 3/12
- **Project Meeting #3** by 03/18 Thursday 11:59 PM (PDT)

- **Project Final Report & Video** due 03/18 Thursday 11:59 PM (PDT)

**Note:**
- Please monitor your AWS credits and idle instances to ensure you’re within your $500 budget!

Kian Katanforoosh