CS540 Introduction to Artificial Intelligence
Lecture 14

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Reinforcement Learning

Motivation

- Reinforcement learning is about learning from the outcome of actions.

1. Sense world.
2. Reason.
3. Choose an action to perform.
4. Get feedback.
5. Learn.

Applications

Motivation

- Actions can be performed in the physical world or artificial ones.
- Board games.
- Robotic control.
- Autonomous helicopter performance.
- Economics models.

Bandits

Motivation

- There are K arms, pulling each arm i results in reward r_i.
- The reward r_i is random and a follows Gaussian distribution with mean reward μ_i and variance $\sigma^2 = 1$.
- Suppose $\mu_1 \geqslant \mu_2 \geqslant \mu_3 \geqslant \ldots \geqslant \mu_K$.

Exploration then Exploitation Algorithm

Motivation

1. Pull each arm t times to estimate the mean reward.

$$\hat{\mu}_{i,t} = \frac{1}{n} \sum_{t'=1}^{t} r_{i,t'}$$

$r_{i,t'}$ is the random reward from arm i and t' -th pull.

2. Pull the arm $i^\star$ with the highest estimated mean reward.

$$i^\star = \arg \max_{i=1,2,\ldots,K} \hat{\mu}_{i,t}$$

Upper Confidence Bound Algorithm

Motivation

1. Pull the arm $i^\star$ with the highest upper confidence bound.

$$i^\star = \arg \max_{i=1,2,\ldots,K} \begin{cases} \text{UCB} = \hat{\mu}_{i,t} + \sqrt{\dfrac{2\log\left(\dfrac{1}{\delta}\right)}{t}} & t > 0 \\ \infty & t = 0 \end{cases}$$

δ is the confidence level parameter.

$$\mathbb{P}\left\{ \mu_i \leqslant \hat{\mu}_{i,t} + \sqrt{\dfrac{2\log\left(\dfrac{1}{\delta}\right)}{t}} \right\} \leqslant 1 - \delta$$

UCB Algorithm Diagram

Motivation

Bandit Applications

Motivation

- Managing research projects.
- Treatment for patients.
- Search engine ranking.
- Wireless adaptive routing.
- Financial portfolio design.

Q Learning

Description

- Select an action.
- Receive reward.
- Observe new state.
- Update (learn) the value of the state-action pair.

State and Actions

Definition

- The set of possible states is $s_t \in S$.
- The set of possible actions is $a_t \in A$.
- The set of possible rewards is $r_t \in R$.
- At each time t :

1. Observe state s_t.
2. Chooses action a_t.
3. Receives reward r_t.
4. Changes to state s_{t+1}.

Markov Decision Process

Definition

- Markov property on states and actions is assumed.

$$\mathbb{P}\left\{s_{t+1} \middle| s_t, a_t, s_{t-1}, a_{t-1}, \ldots\right\} = \mathbb{P}\left\{s_{t+1} \middle| s_t, a_t\right\}$$
$$\mathbb{P}\left\{r_{t+1} \middle| s_t, a_t, s_{t-1}, a_{t-1}, \ldots\right\} = \mathbb{P}\left\{r_{t+1} \middle| s_t, a_t\right\}$$

- The goal is to learn a policy function $\pi : S \to A$ for choosing actions that maximize the total expected discounted reward.

$$\mathbb{E}\left[r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \ldots\right], \gamma \in [0, 1]$$

Expected Reward

Definition

- The expected reward at a given time t is the average reward weighted by probabilities.

$$\mathbb{E}\left[r_t\right] = \sum_{r_t \in R} r_t \mathbb{P}\left\{r_t \middle| s_{t-1}, a_{t-1}\right\}$$

Discounted Reward

Definition

- The discounted reward at time 0 is the sum of reward weighted given the time preference, usually described by a constant discount factor.

$$\text{PV}\ (r_t) = \gamma^t r_t, \gamma \in [0, 1]$$

$$\text{PV}\ (r_1, r_2, ...) = \sum_{t=0}^{\infty} \gamma^t r_t$$

- γ is the value of 1 unit of reward at time 1 perceived at time 0. If $\gamma = 1$, the sum over an infinite time period is usually infinity, therefore $\gamma < 1$ is usually used.

Value Function

Definition

- The value function is the expected discounted reward given a policy function π, assuming the action sequence is chosen according to π stating with state s.

$$V^{\pi}(s) = \sum_{t=0}^{\infty} \gamma^t \mathbb{E}[r_t]$$

- The optimal policy $\pi^\star$ is the one that maximizes the value function.

$$\pi^\star = \arg\max_{\pi} V^{\pi}(s) \text{ for all } s \in S$$
$$V^\star(s) = V^{\pi^\star}(s)$$

Goal Learning Example, Part I

Definition

Goal Learning Example, Part II

Definition

Optimal Policy Given Value Function

Definition

- Given $V^\star(s), r(s,a), \mathbb{P}(s'|s,a), \pi^\star$ can be computed directly.

$$\begin{aligned}\pi^\star(s) &= \arg\max_{a\in A}\left(\mathbb{E}[r|s,a] + \gamma\mathbb{E}\left[V^\star(s')|s,a\right]\right)\\ &= \arg\max_{a\in A}\left(\sum_{r\in R} r\mathbb{P}\{r|s,a\} + \gamma\sum_{s'\in S}\mathbb{P}\{s'|s,a\}V^\star(s')\right)\end{aligned}$$

- Define the function inside the arg max as the Q function.

Q Function

Definition

$$V^{\star}(s) = \mathbb{E}\left[r | s, \pi^{\star}(s)\right] + \gamma \mathbb{E}\left[V^{\star}\left(s'\right) | s, \pi^{\star}(s)\right]$$
$$Q(s, a) = \mathbb{E}\left[r | s, a\right] + \gamma \mathbb{E}\left[V^{\star}\left(s'\right) | s, a\right]$$

- If the agent knows Q, then the optimal action can be learned without $\mathbb{P}\left\{s' | s, a\right\}$.

$$\pi^{\star}(s) = \arg\max_{a} Q(s, a), V^{\star}(s) = \max_{a} Q(s, a)$$

Deterministic Q Learning

Definition

- In the deterministic case, $\mathbb{P}\left\{s' \middle| s, a\right\}$ is either 0 or 1, the update formula for the Q function is the following.

$$\hat{Q}\left(s, a\right) = r + \gamma \max_{a'} \hat{Q}\left(s', a'\right)$$

Q Learning Example, Part I

Definition

Q Learning Example, Part II

Definition

Non-Deterministic Q Learning

Definition

- In the nondeterministic case, the update formula for the Q function is the following.

$$\hat{Q}(s,a) = (1-\alpha)\,\hat{Q}(s,a) + \alpha\left(r + \gamma \max_{a'} \hat{Q}(s',a')\right)$$

$$\alpha = \frac{1}{1 + \text{ visits } (s,a)}$$

- Q learning will converge to the correct Q function in both deterministic and non-deterministic cases. In practice, it takes a very large number of iterations.

Q Learning, Part I

Algorithm

- Input: the state and reward processes.
- Output: optimal policy function $\pi^{\star}(s)$
- Initialize the Q table.

$$\hat{Q}(s, a) = 0, \text{ for each } s \in S, a \in A$$

Q Learning, Part II

Algorithm

- Observe current state s.
- Select an action a and execute it.
- Receive immediate reward r.
- Observe the new state s'.
- Update the table entry.

$$\hat{Q}(s,a) = (1-\alpha)\,\hat{Q}(s,a) + \alpha\left(r + \gamma \max_{a'} \hat{Q}(s',a')\right)$$

$$\alpha = \frac{1}{1 + \text{ visits } (s,a)}$$

- Update the state and repeat forever.

$$s = s'$$

Exploration vs Exploitation

Discussion

- There is a trade-off between learning about possibly better alternatives and following the current policy. Sometimes, random actions should be selected.

$$\mathbb{P}\left\{a \middle| s\right\} = \frac{c^{\hat{Q}(s,a)}}{\sum\limits_{a' \in A} c^{\hat{Q}(s,a')}}$$

- $c > 0$ is a constant that determines how strongly selection favors actions with higher Q values.

Q Table vs Q Net

Discussion

- In practice, Q table is too large to store since the number of possible states is very large.
- If there are m binary features that represent the state, the Q table contains $2^m \left|A\right|$.
- However, it can be stored in a neural network called Q net.
- If there is a single hidden layer with m units, there are only $m^2 + m \left|A\right|$ weights to store.

Q Net Diagram

Discussion

Q Net Training

Discussion

- Observe the features x given a state s.
- Apply action a and observe new state s' with features x' and reward r.
- Train the network with new instance (x, y)

$$y = (1 - \alpha)\,\hat{y}\,(x, a) + \alpha \left(r + \gamma \max_{a'} \hat{y}\,(x', a') \right)$$

- $\hat{y}\,(x, a)$ is the activation of output unit a given the input x in the current neural network.
- $\hat{y}\,(x', a')$ is the activation output unit a' given the input x' in the current neural network.

Multi-Agent Learning

Discussion

- Value function and policy function iteration methods can be applied to solve dynamic games with multiple agents.
- It will be used again in game theory in Week 11.