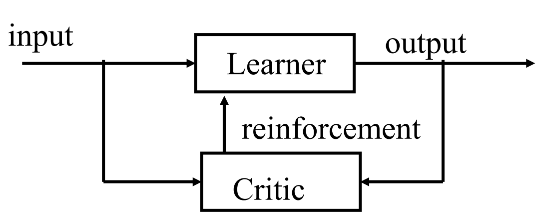
CS 2750 Machine Learning
Lecture 20

Reinforcement learning

Milos Hauskrecht
milos@cs.pitt.edu
5329 Sennott Square

Reinforcement learning

- **We want to learn the control policy:** $\pi : X \to A$
- We see examples of **x** (but outputs a are not given)
- Instead of a we get a feedback (reinforcement, reward) from a **critic** quantifying how good the selected output was



- The reinforcements may not be deterministic
- **Goal:** find $\pi : X \to A$ with the best expected reinforcements

Gambling example.

- **Game:** 3 different biased coins are tossed
  - The coin to be tossed is selected randomly from the three options and I always see which coin I am going to play next
  - I make bets on head or tail and I always wage $1
  - If I win I get $1, otherwise I lose my bet
- **RL model:**
  - **Input:** X – a coin chosen for the next toss,
  - **Action:** A – choice of head or tail,
  - **Reinforcements:** {1, -1}
- **A policy** $\pi : X \rightarrow A$

  Example: $\pi : \left| \begin{array}{l} \textbf{Coin1} \longrightarrow \textbf{\textit{head}} \\ \textbf{Coin2} \longrightarrow \textbf{\textit{tail}} \\ \textbf{Coin3} \longrightarrow \textbf{\textit{head}} \end{array} \right|$

Gambling example

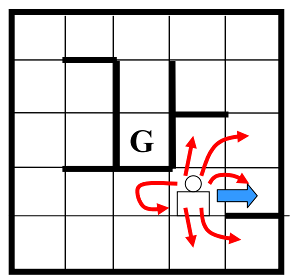
- **RL model:**
  - **Input:** X – a coin chosen for the next toss,
  - **Action:** A – choice of head or tail,
  - **Reinforcements:** {1, -1}
  - **A policy** $\pi : \left| \begin{array}{l} \textbf{Coin1} \longrightarrow \textbf{\textit{head}} \\ \textbf{Coin2} \longrightarrow \textbf{\textit{tail}} \\ \textbf{Coin3} \longrightarrow \textbf{\textit{head}} \end{array} \right|$
- **Learning goal: find** $\pi : X \rightarrow A$ $\quad \pi : \left| \begin{array}{l} \textbf{Coin1} \longrightarrow \textbf{?} \\ \textbf{Coin2} \longrightarrow \textbf{?} \\ \textbf{Coin3} \longrightarrow \textbf{?} \end{array} \right|$

  maximizing future expected profits

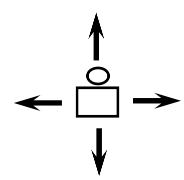
  $E(\sum_{t=0}^{\infty} \gamma^t r_t)$ $\quad \gamma$ a discount factor = present value of money

Agent navigation example.

- **Agent navigation in the Maze**:
  - 4 moves in compass directions
  - Effects of moves are stochastic – we may wind up in other than intended location with non-zero probability
  - **Objective:** reach the goal state in the shortest expected time

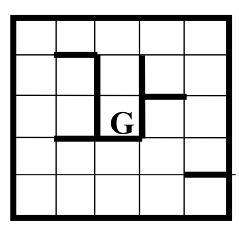


moves

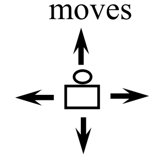


Agent navigation example

- **The RL model:**
  - **Input:** X – position of an agent
  - **Output:** A –a move
  - **Reinforcements:** R
    - -1 for each move
    - +100 for reaching the goal
  - **A policy:** $\pi : X \rightarrow A$



moves



π: **Position 1** → ***right***
Position 2 → ***right***
…
Position 20 → ***left***

- **Goal:** **find the policy maximizing future expected rewards**

$$E\left(\sum_{t=0}^{\infty} \gamma^t r_t\right)$$

Objectives of RL learning

- **Objective:**
  Find a mapping $\pi^* : X \rightarrow A$
  That maximizes some combination of future reinforcements (rewards) received over time
- **Valuation models (quantify how good the mapping is):**
  – **Finite horizon model**
  $$E(\sum_{t=0}^{T} r_t) \qquad \text{Time horizon: } T > 0$$
  – **Infinite horizon discounted model**
  $$E(\sum_{t=0}^{\infty} \gamma^t r_t) \qquad \text{Discount factor: } 0 < \gamma < 1$$
  – **Average reward**
  $$\lim_{T \to \infty} \frac{1}{T} E(\sum_{t=0}^{T} r_t)$$

Exploration vs. Exploitation

- The (learner) actively interacts with the environment:
  – At the beginning the learner does not know anything about the environment
  – It gradually gains the experience and learns how to react to the environment
- **Dilemma (exploration-exploitation):**
  – After some number of steps, should I select the best current choice (**exploitation**) or try to learn more about the environment (**exploration**)?
  – **Exploitation** may involve the selection of a sub-optimal action and prevent the learning of the optimal choice
  – **Exploration** may spend to much time on trying bad currently suboptimal actions

Effects of actions on the environment

Effect of actions on the environment (next input **x** to be seen)

- No effect, the distribution over possible **x** is fixed; action consequences (rewards) are seen immediately,
- Otherwise, distribution of **x** can change; the rewards related to the action can be seen with some delay.

Leads to two forms of **reinforcement learning:**

- **Learning with immediate rewards**
  - **Gambling example**
- **Learning with delayed rewards**
  - **Agent navigation example**; move choices affect the state of the environment (position changes), a big reward at the goal state is delayed

RL with immediate rewards.

- **Game:** 3 different biased coins are tossed
  - The coin to be tossed is selected randomly from the three options and I always see which coin I am going to play next
  - I make bets on head or tail and I always wage \$1
  - If I win I get \$1, otherwise I lose my bet
- **RL model:**
  - **Input:** X – a coin chosen for the next toss
  - **Action:** A – head or tail bet
  - **Reinforcements:** {1, -1}
- **Learning goal: find** $\pi : X \rightarrow A$

  maximizing the future expected profits over time

  $E(\sum_{t=0}^{\infty} \gamma^t r_t)$ γ a discount factor = present value of money

RL with immediate rewards

- **Expected reward**

$$E(\sum_{t=0}^{\infty} \gamma^t r_t) \quad \gamma \text{ - a discount factor = present value of money}$$

- **Immediate reward case:**
  - Reward for the choice becomes available immediately
  - Our choice does not affect environment and thus future rewards

$$E(\sum_{t=0}^{\infty} \gamma^t r_t) = E(r_0) + E(\gamma r_1) + E(\gamma^2 r_2) + \dots$$

$r_0, r_1, r_2 \dots$ Rewards for every step

  - Expected one step reward for input $\mathbf{x}$ and the choice a : $R(\mathbf{x}, a)$

RL with immediate rewards

Immediate reward case:

- Reward for the choice a becomes available immediately
- Expected reward for the input $\mathbf{x}$ and choice a: $R(\mathbf{x}, a)$
  - For the gambling problem it can be defined as:

$$R(\mathbf{x}, a_i) = \sum_j r(\omega_j \mid a_i, \mathbf{x}) P(\omega_j \mid \mathbf{x}, a_i)$$

  - ω_j - a "hidden" outcome of the coin toss
  - Recall the definition of the expected loss
- **Expected one step reward for a strategy** $\pi : X \to A$

$$R(\pi) = \sum_x R(\mathbf{x}, \pi(\mathbf{x})) P(\mathbf{x})$$

$R(\pi)$ is the expected reward for $r_0, r_1, r_2 \dots$

RL with immediate rewards

- **Expected reward**

$$E(\sum_{t=0}^{\infty} \gamma^t r_t) = E(r_0) + E(\gamma r_1) + E(\gamma^2 r_2) + \dots$$

- **Optimizing the expected reward :**

$$\max_\pi E(\sum_{t=0}^{\infty} \gamma^t r_t) = \max_\pi \sum_{t=0}^{\infty} \gamma^t E(r_t) = \max_\pi \sum_{t=0}^{\infty} \gamma^t R(\pi) = \max_\pi R(\pi)(\sum_{t=0}^{\infty} \gamma^t)$$

$$= (\sum_{t=0}^{\infty} \gamma^t) \max_\pi R(\pi)$$

$$\max_\pi R(\pi) = \max_\pi \sum_x R(\mathbf{x}, \pi(\mathbf{x})) P(\mathbf{x}) = \sum_x P(\mathbf{x})[\max_{\pi(\mathbf{x})} R(\mathbf{x}, \pi(\mathbf{x}))]$$

- **Optimal strategy:** $\pi^*: X \to A$

$$\pi^*(\mathbf{x}) = \arg\max_a R(\mathbf{x}, a)$$

RL with immediate rewards

- **We know that** $\pi^*(\mathbf{x}) = \arg\max_a R(\mathbf{x}, a)$
- **Problem:** In the RL framework we do not know $R(\mathbf{x}, a)$
  - The expected reward for performing action a at input $\mathbf{x}$
- **How to get** $R(\mathbf{x}, a)$ **?**

RL with immediate rewards

- **Problem:** In the RL framework we do not know $R(\mathbf{x}, a)$
  - The expected reward for performing action a at input $\mathbf{x}$
- **Solution:**
  - For each input $\mathbf{x}$ try different actions a
  - Estimate $R(\mathbf{x}, a)$ using the average of observed rewards

$$\tilde{R}(\mathbf{x}, a) = \frac{1}{N_{x,a}} \sum_{i=1}^{N_{x,a}} r_i^{x,a}$$

  - Action choice $\pi(\mathbf{x}) = \arg\max_a \tilde{R}(\mathbf{x}, a)$
  - Accuracy of the estimate: statistics (Hoeffding's bound)

$$P\left(\left|\tilde{R}(\mathbf{x}, a) - R(\mathbf{x}, a)\right| \geq \varepsilon\right) \leq \exp\left[-\frac{2\varepsilon^2 N_{x,a}}{(r_{\max} - r_{\min})^2}\right] \leq \delta$$

  - Number of samples: $N_{x,y} \geq \frac{(r_{\max} - r_{\min})^2}{2\varepsilon^2} \ln \frac{1}{\delta}$

RL with immediate rewards

- **On-line (stochastic approximation)**
  - An alternative way to estimate $R(\mathbf{x}, a)$
- **Idea:**
  - choose action a for input $\mathbf{x}$ and observe a reward $r^{x,a}$
  - Update an estimate

$$\boxed{\tilde{R}(\mathbf{x}, a) \leftarrow (1-\alpha)\tilde{R}(\mathbf{x}, a) + \alpha\, r^{x,a}}$$

α - a learning rate

- **Convergence property:** The approximation converges in the limit for an appropriate learning rate schedule.
- Assume: $\alpha(n(x,a))$ - is a learning rate for *n*th trial of (x,a) pair
- Then the converge is assured if:

1. $\sum_{i=1}^{\infty} \alpha(i) = \infty$ 2. $\sum_{i=1}^{\infty} \alpha(i)^2 < \infty$

Exploration vs. Exploitation

- In the RL framework
  - the (learner) actively interacts with the environment.
  - At any point in time it has an estimate of $\tilde{R}(\mathbf{x}, a)$ for any input action pair
- **Dilemma:**
  - Should the learner use the current best choice of action (exploitation)

$$\hat{\pi}(\mathbf{x}) = \arg\max_{a \in A} \tilde{R}(\mathbf{x}, a)$$

  - Or choose other action a and further improve its estimate (exploration)

- **Different exploration/exploitation strategies exist**

Exploration vs. Exploitation

- **Uniform exploration**
  - Choose the "current" best choice with probability $1-\varepsilon$

$$\hat{\pi}(\mathbf{x}) = \arg\max_{a \in A} \tilde{R}(\mathbf{x}, a)$$

  - All other choices are selected with a uniform probability

$$\frac{\varepsilon}{|A|-1}$$

- **Boltzman exploration**
  - The action is chosen randomly but proportionally to its current expected reward estimate

$$p(a \mid \mathbf{x}) = \frac{\exp\left[\tilde{R}(x,a)/T\right]}{\sum_{a' \in A} \exp\left[\tilde{R}(x,a')/T\right]}$$

T – is temperature parameter. **What does it do?**