Reinforcement Learning

Monte Carlo Methods

Stefano Albrecht, Pavlos Andreadis

28 January 2020

THE UNIVERSITY of EDINBURGH
informatics

Lecture Outline

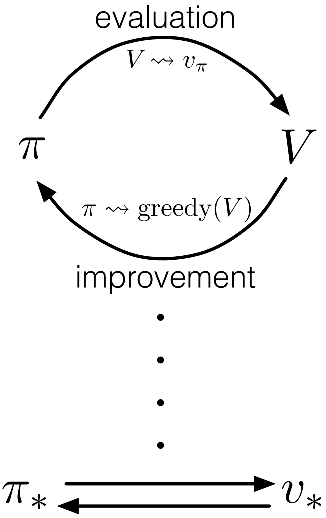
- Monte Carlo policy evaluation
- Monte Carlo control with...
  - Exploring starts
  - Soft policies
  - Off-policy learning

Recap: Generalised Policy Iteration

DP methods iterate through policy evaluation and improvement until convergence to optimal value function v_* and policy π_*

- Policy evaluation via repeated application of Bellman operator
- Requires complete knowledge of MDP model: $p(s', r|s, a)$

Can we compute optimal policy without knowledge of complete model?



Monte Carlo Policy Evaluation

Monte Carlo (MC) methods learn value function based on experience

- Experience: entire episodes $E^i = < S_0^i, A_0^i, R_1^i, S_1^i, A_1^i, R_2^i, ..., S_{T_i}^i >$

Two ways to obtain episodes:

- **Real experience:** generate episodes directly from “real world”
- **Simulated experience:** use simulation model $\hat{p}$ to sample episodes
  - $\hat{p}(s, a)$ returns a pair (s', r) with probability $p(s', r|s, a)$

MC does not require complete model $p(s', r|s, a)$

Monte Carlo Policy Evaluation

Monte Carlo (MC) methods **learn** value function based on **experience**

- Estimate value function by averaging sample returns:

$$v_\pi(s) \doteq \mathbb{E}_\pi\left[\sum_{k=0}^{T-1} \gamma^k R_{k+1} | S_t = s\right] \approx \frac{1}{|\mathcal{E}(s)|} \sum_{t_i \in \mathcal{E}(s)} \sum_{k=t_i}^{T_i-1} \gamma^{k-t} R^i_{k+1}$$

  where for each past episode $E^i = < S^i_0, A^i_0, R^i_1, S^i_1, A^i_1, R^i_2, \ldots, S^i_{T_i} >$:

  - **First-visit MC:** $\mathcal{E}(s)$ contains *first* time t_i for which $S^i_{t_i} = s$ in E^i
  - **Every-visit MC:** $\mathcal{E}(s)$ contains *all* times t_i for which $S^i_{t_i} = s$ in E^i

- Both methods converge to $v_\pi(s)$ as $|\mathcal{E}(s)| \to \infty$

First-Visit Monte Carlo Policy Evaluation

Initialize:

$\pi \leftarrow$ policy to be evaluated

$V \leftarrow$ an arbitrary state-value function

$Returns(s) \leftarrow$ an empty list, for all $s \in \mathcal{S}$

Repeat forever:

Generate an episode using π

For each state s appearing in the episode:

$G \leftarrow$ return following the first occurrence of s

Append G to $Returns(s)$

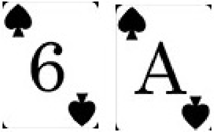
$V(s) \leftarrow \text{average}(Returns(s))$

Example: Blackjack

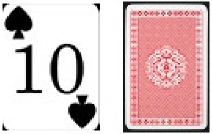
Initial state:

Player

Ace worth 1 or 11



Dealer



Hidden card

First, player samples cards from deck (hit) until stop (stick)

Then, dealer samples cards from deck (hit) until sum > 16 (stick)

Player loses (-1 reward) if bust (card sum > 21)
Player wins (+1 reward) if Dealer bust or Player sum > Dealer sum

Example: Blackjack

Player policy π:

stick if player sum is
20 or 21, else hit

Estimate of v_π using MC ...

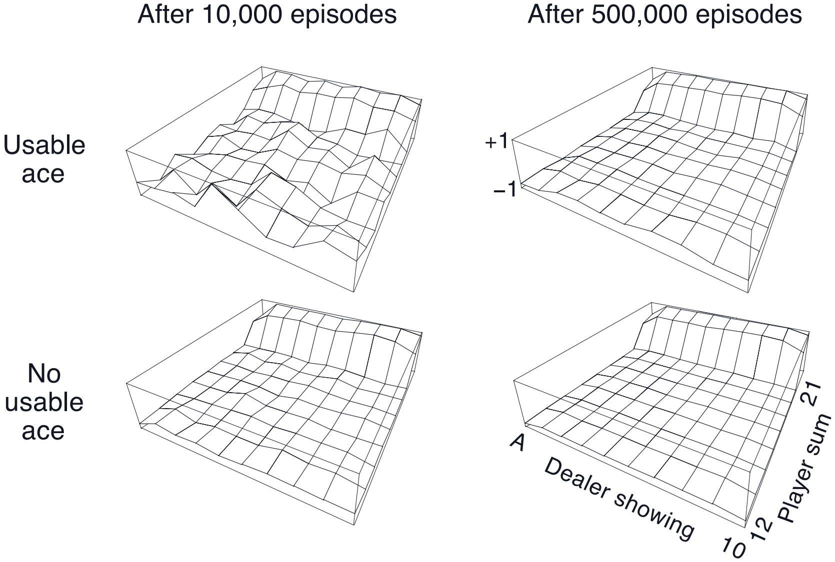
States (3-tuple):
– Player sum (12–21)
– Dealer card (ace–10)
– Usable ace?

Player policy π:

stick if player sum is 20 or 21, else hit

States (3-tuple):

- Player sum (12–21)
- Dealer card (ace–10)
- Usable ace?



States in Blackjack

Couldn't we just define states as $S_t = \{\text{Player cards, Dealer card}\}$?

- Tricky: states would have variable length (player cards)
- If we fix maximum number of player cards to 4, then there are $10^5 = 100,000$ possible states! (ignoring face cards and ordering)

States in Blackjack

Couldn't we just define states as $S_t = \{\text{Player cards, Dealer card}\}$?

- Tricky: states would have variable length (player cards)
- If we fix maximum number of player cards to 4, then there are $10^5 = 100,000$ possible states! (ignoring face cards and ordering)

Blackjack example uses engineered state features:

- Fixed length: $S_t = (\text{Player sum, Dealer card, Usable ace?})$
- Player sum limited to range 12–21 because decision below 12 is trivial (always hit)
- Number of states: $10 * 10 * 2 = 200 \rightarrow$ much smaller problem!
- Still has all relevant information

Blackjack and Dynamic Programming

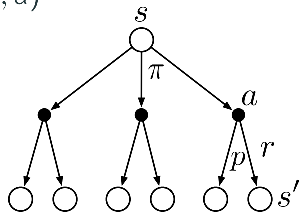
Can we solve Blackjack MDP with DP methods?

- Yes, in principle, because we know complete MDP
- But computing $p(s', r|s, a)$ can be complicated!
  E.g. what is probability of $+1$ reward as function of Dealer's showing card?
- On other hand, easy to code a simulation model:
  — Use Dealer rule to sample cards until stick/bust, then compute reward
  — Reward outcome is distributed by $p(s', r|s, a)$
- MC can evaluate policy without knowledge of probabilities $p(s', r|s, a)$

Monte Carlo Estimation of Action Values

MC methods can learn v_π without knowledge of model $p(s', r|s, a)$

$\Rightarrow$ But improving policy π from v_π requires model *(why?)*



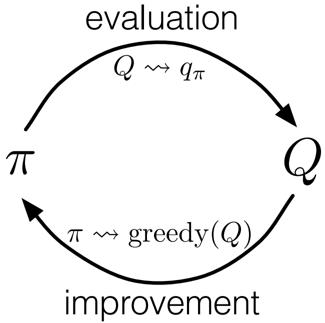
Must estimate action values:

$$q_\pi(s, a) \doteq \mathbb{E}_\pi[G_t | S_t = s, A_t = a]$$

- Improve policy without model: $\pi'(s) = \arg\max_a q_\pi(s, a)$
- Use same MC methods to learn q_π, but visits are to (s, a) pairs
- Converges to q_π if every (s, a) pair visited infinitely many times in limit

  E.g. exploring starts: every (s, a) pair has non-zero probability of being starting pair of episode

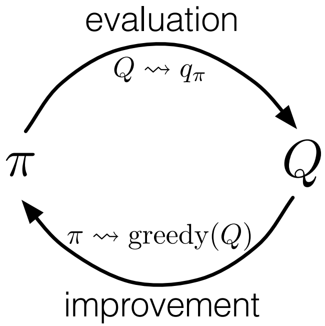
- **MC policy evaluation:**
  Estimate q_π using MC method
- **Policy improvement:**
  Improve π by making greedy wrt q_π



Monte Carlo Control with Exploring Starts

Greedy policy meets conditions for policy improvement theorem:

$$\begin{aligned} q_{\pi_k}(s, \pi_{k+1}(s)) &= q_{\pi_k}(s, \arg\max_a q_{\pi_k}(s, a)) \\ &= \max_a q_{\pi_k}(s, a) \\ &\geq q_{\pi_k}(s, \pi_k(s)) \\ &= v_{\pi_k}(s) \end{aligned}$$



Assumes exploring starts and *infinite* MC iterations *(why?)*

- In practice, update only to a given performance threshold
- Or alternate between evaluation and improvement per episode

Monte Carlo Control with Exploring Starts

Initialize, for all $s \in \mathcal{S}$, $a \in \mathcal{A}(s)$:

$Q(s, a) \leftarrow$ arbitrary

$\pi(s) \leftarrow$ arbitrary

$Returns(s, a) \leftarrow$ empty list

Repeat forever:

Choose $S_0 \in \mathcal{S}$ and $A_0 \in \mathcal{A}(S_0)$ s.t. all pairs have probability > 0

Generate an episode starting from S_0, A_0, following π

For each pair s, a appearing in the episode:

$G \leftarrow$ return following the first occurrence of s, a

Append G to $Returns(s, a)$

$Q(s, a) \leftarrow$ average$(Returns(s, a))$

For each s in the episode:

$\pi(s) \leftarrow \arg\max_a Q(s, a)$

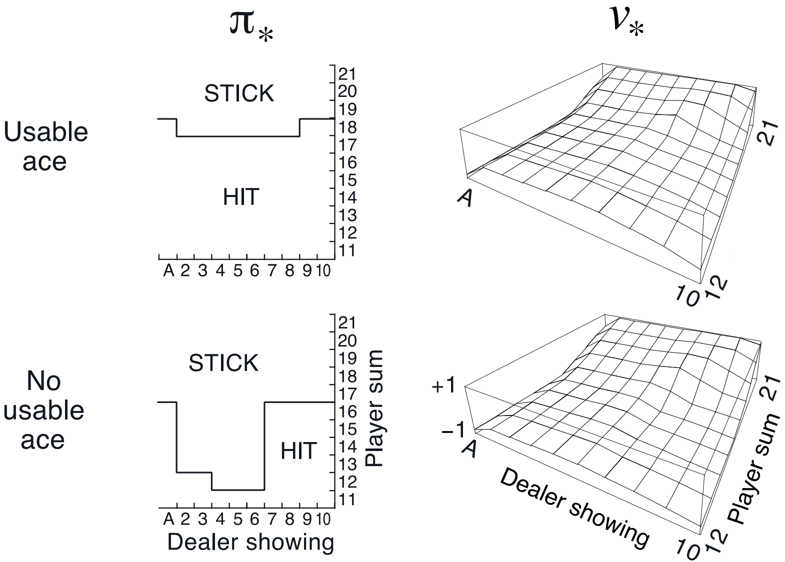
Blackjack Example with MC–ES

Policy π:

stick if player sum is 20 or 21, else hit

Exploring starts:

sample initial states uniformly randomly



Monte Carlo Control With Soft Policies

Convergence to q_π requires that all (s, a)-pairs are visited infinitely many times

- Exploring starts guarantee this, but impractical *(why?)*

Other approach: use soft policy such that $\pi(a|s) > 0$ for all s, a

- e.g. ϵ-soft policy: $\pi(a|s) \geq \epsilon/|\mathcal{A}|$ for $\epsilon > 0$
- **Policy improvement:** make policy ϵ-greedy wrt q_π

$$\pi'(a|s) \doteq \begin{cases} \epsilon/|\mathcal{A}| + (1-\epsilon) & \text{if } a = \arg\max_{a'} q_\pi(s, a') \\ \epsilon/|\mathcal{A}| & \text{else} \end{cases}$$

Monte Carlo Control With Soft Policies

ϵ-greedy policy meets conditions for policy improvement theorem:

$$
\begin{aligned}
q_\pi(s, \pi'(s)) &= \sum_a \pi'(a|s)\, q_\pi(s,a) \\
&= \frac{\epsilon}{|\mathcal{A}|} \sum_a q_\pi(s,a) + (1-\epsilon) \max_a q_\pi(s,a) \\
&\geq \frac{\epsilon}{|\mathcal{A}|} \sum_a q_\pi(s,a) + (1-\epsilon) \sum_a \frac{\pi(a|s) - \epsilon/|\mathcal{A}|}{1-\epsilon} q_\pi(s,a) \\
&= \frac{\epsilon}{|\mathcal{A}|} \sum_a q_\pi(s,a) - \frac{\epsilon}{|\mathcal{A}|} \sum_a q_\pi(s,a) + \sum_a \pi(a|s)\, q_\pi(s,a) \\
&= v_\pi(s)
\end{aligned}
$$

- Thus, π' better or equal to π, but both are still ϵ-soft
- $q_\pi(s, \pi'(s)) = v_\pi(s)$ only when π' and π both optimal ϵ-soft policies

Monte Carlo Control With Soft Policies

Initialize, for all $s \in \mathcal{S}$, $a \in \mathcal{A}(s)$:

$Q(s,a) \leftarrow$ arbitrary

$Returns(s,a) \leftarrow$ empty list

$\pi(a|s) \leftarrow$ an arbitrary ε-soft policy

Repeat forever:

(a) Generate an episode using π

(b) For each pair s, a appearing in the episode:

$G \leftarrow$ return following the first occurrence of s, a

Append G to $Returns(s,a)$

$Q(s,a) \leftarrow \text{average}(Returns(s,a))$

(c) For each s in the episode:

$A^* \leftarrow \arg\max_a Q(s,a)$

For all $a \in \mathcal{A}(s)$:

$$\pi(a|s) \leftarrow \begin{cases} 1 - \varepsilon + \varepsilon/|\mathcal{A}(s)| & \text{if } a = A^* \\ \varepsilon/|\mathcal{A}(s)| & \text{if } a \neq A^* \end{cases}$$

Off-Policy Methods

Like exploring starts, soft policies ensure all (s, a) are visited infinitely many times

- But policies restricted to be soft

  $\Rightarrow$ Optimal policy is usually deterministic!
- Could slowly reduce ϵ, but not clear how fast

Other approach: off-policy learning

- Learn q_π based on experience generated with *behaviour policy* $\mu \neq \pi$
- Requires "coverage": if $\pi(a|s) > 0$ then $\mu(a|s) > 0$, for all s, a

  — e.g. use soft policy μ
- π can be deterministic

Discussion: On-Policy vs Off-Policy Methods

On-policy:

Learn q_π and improve π while following π

Off-policy:

Learn q_π and improve π while following μ

Importance Sampling Ratio

We have episodes generated from μ

$\Rightarrow$ Expected return at t is $\mathbb{E}_\mu[G_t | S_t = s] = v_{\mu}(s)$

Fix expectation with sampling importance ratio:

$$\rho_{t:T} \doteq \frac{\prod_{k=t}^{T-1} \pi(A_k|S_k)\, p(S_{k+1}, R_{k+1}|S_k, A_k)}{\prod_{k=t}^{T-1} \mu(A_k|S_k)\, p(S_{k+1}, R_{k+1}|S_k, A_k)} = \prod_{k=t}^{T-1} \frac{\pi(A_k|S_k)}{\mu(A_k|S_k)}$$

- $\mathbb{E}_\mu[\rho_{t:T}\, G_t | S_t = s] = v_{\pi}(s)$

Importance Sampling Ratio

$$
\begin{aligned}
\mathbb{E}_{\mu}[\rho_{t:T}\, G_t | S_t = s] &= \sum_{E:S_t=s} \left[\prod_{k=t}^{T-1} \mu(A_k|S_k)\, p(S_{k+1}, R_{k+1}|S_k, A_k)\right] \rho_{t:T}\, G_t \\
&= \sum_{E:S_t=s} \left[\prod_{k=t}^{T-1} \mu(A_k|S_k)\, p(S_{k+1}, R_{k+1}|S_k, A_k)\right] \prod_{k=t}^{T-1} \frac{\pi(A_k|S_k)}{\mu(A_k|S_k)}\, G_t \\
&= \sum_{E:S_t=s} \left[\prod_{k=t}^{T-1} \pi(A_k|S_k)\, p(S_{k+1}, R_{k+1}|S_k, A_k)\right] G_t \\
&= v_{\pi}(s)
\end{aligned}
$$

Evaluating Policies with Importance Sampling

Denote episodes $E^i = < S_0^i, A_0^i, R_1^i, S_1^i, A_1^i, R_2^i, ..., S_{T_i}^i >$

Define $\mathcal{E}(s)/\mathcal{E}(s,a)$ as before for first-visit or every-visit MC

Estimate v_π/q_π as

$$v_\pi(s) \approx \eta^{-1} \sum_{t_i \in \mathcal{E}(s)} \rho_{t_i:T_i} G_{t_i}^i$$

$$q_\pi(s,a) \approx \eta^{-1} \sum_{t_i \in \mathcal{E}(s,a)} \rho_{t_i+1:T_i} G_{t_i}^i$$

- **Ordinary** importance sampling: $\eta = |\mathcal{E}(s,a)|$
- **Weighted** importance sampling: $\eta = \sum_{t_i \in \mathcal{E}(s)} \rho_{t_i:T_i}$ resp. $\eta = \sum_{t_i \in \mathcal{E}(s,a)} \rho_{t_i+1:T_i}$

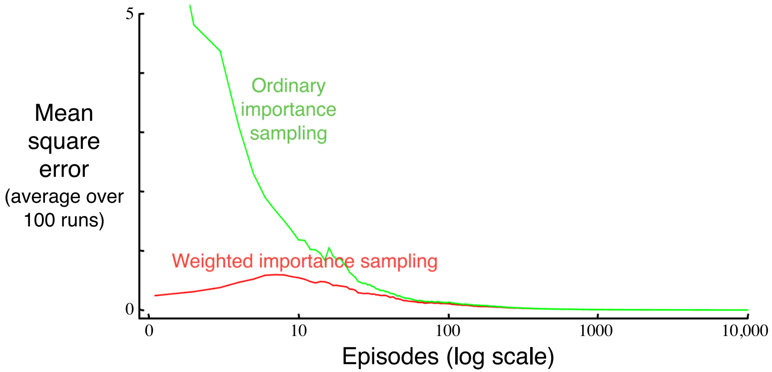
Off-Policy Value Estimation in Blackjack Example

π : stick if player sum is 20 or 21, else hit

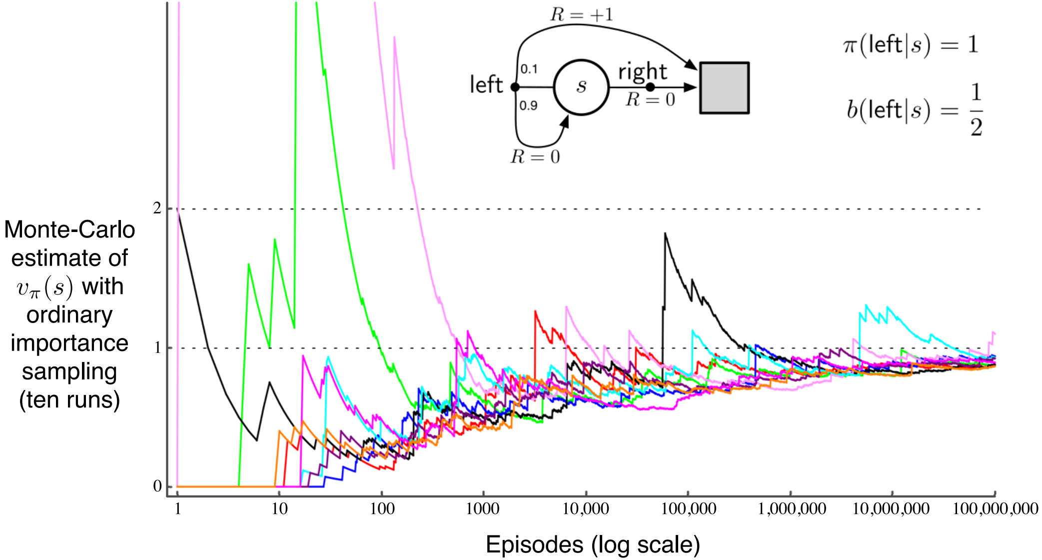
μ : uniformly random

s : player sum 13
dealer showing 2
usable ace

True value:
$v_\pi(s) \approx -0.27726$



Infinite Variance in Ordinary Importance Sampling



Iterative Implementation of Weighted Importance Sampling

Input: an arbitrary target policy π
Initialize, for all $s \in \mathcal{S}$, $a \in \mathcal{A}(s)$:
    $Q(s,a) \in \mathbb{R}$ (arbitrarily)
    $C(s,a) \leftarrow 0$

Loop forever (for each episode):
    $b \leftarrow$ any policy with coverage of π
    Generate an episode following b: $S_0, A_0, R_1, \ldots, S_{T-1}, A_{T-1}, R_T$
    $G \leftarrow 0$
    $W \leftarrow 1$
    Loop for each step of episode, $t = T-1, T-2, \ldots, 0$, while $W \neq 0$:
        $G \leftarrow \gamma G + R_{t+1}$
        $C(S_t, A_t) \leftarrow C(S_t, A_t) + W$
        $Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \frac{W}{C(S_t,A_t)}\left[G - Q(S_t, A_t)\right]$
        $W \leftarrow W \frac{\pi(A_t|S_t)}{b(A_t|S_t)}$

Off-Policy Monte Carlo Control

Initialize, for all $s \in \mathcal{S}$, $a \in \mathcal{A}(s)$:

$Q(s,a) \in \mathbb{R}$ (arbitrarily)

$C(s,a) \leftarrow 0$

$\pi(s) \leftarrow \arg\max_a Q(s,a)$ (with ties broken consistently)

Loop forever (for each episode):

$b \leftarrow$ any soft policy

Generate an episode using b: $S_0, A_0, R_1, \ldots, S_{T-1}, A_{T-1}, R_T$

$G \leftarrow 0$

$W \leftarrow 1$

Loop for each step of episode, $t = T-1, T-2, \ldots, 0$:

$G \leftarrow \gamma G + R_{t+1}$

$C(S_t, A_t) \leftarrow C(S_t, A_t) + W$

$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \frac{W}{C(S_t,A_t)} [G - Q(S_t, A_t)]$

$\pi(S_t) \leftarrow \arg\max_a Q(S_t, a)$ (with ties broken consistently)

Why?
Hint: π deterministic
Hint: $q_\pi(s,a)$ uses $\rho_{t+1:T}$

$\left\{ \begin{array}{l} \text{If } A_t \neq \pi(S_t) \text{ then exit inner Loop (proceed to next episode)} \\ W \leftarrow W \frac{1}{b(A_t|S_t)} \end{array} \right.$

Reading

Required:

- RL book, chapter 5 (5.1–5.7)

Optional:

- *Sequential Monte Carlo Methods in Practice*
  Arnaud Doucet, Nando de Freitas, Neil Gordon (editors)
  University library has copies