NOKIA Bell Labs

Reinforcement Learning
Deep Reinforcement Learning

Mathieu Goutay, Nokia Bell Labs

mathieu.goutay@nokia.com

INSA Lyon, France

NOKIA Bell Labs

Follow the course at

[mgoutay.github.io]

→Blog → Machine Learning Course

(Deep) Reinforcement Learning

Lesson

Slides are available $\boxed{\text{here}}$

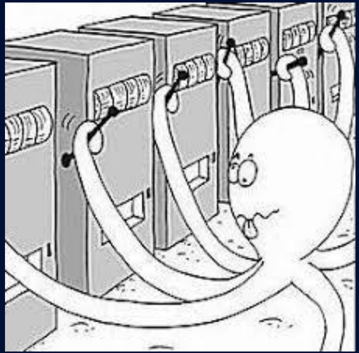
1. Reinforcement Learning, part I
    1. Multi-armed Bandits
    2. Action, reward, action-value, estimated action-value
    3. Policies
    4. Your turn ☺
2. Renforcement Learning, part II
    1. Classic RL problem and Markov Decision Process
    2. Return, state-value, action-value
    3. Temporal Difference Learning
    4. Your turn ☺
3. Deep Reinforcement Leaning
    1. Q-network
    2. Experience replay
    3. Target Network
    4. Your turn ☺

Reinforcement Learning, Part I
Multi-armed Bandit

Problem formulation:

- You have a Wi-Fi network with 7 different channels
- You need to transmit 10.000 packets

→ Which channel do you choose?



Framework:

- For each attempt, you choose a channel (action)
- If the packet was sent, you got a reward : 1
- If there was a collision, you got no reward : 0

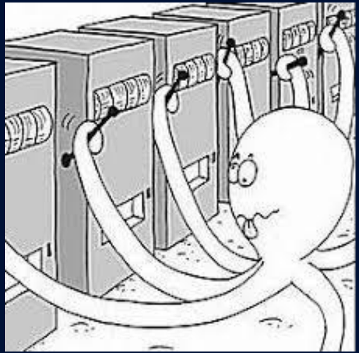
Goal: Online training

→ Find the best action to maximize the total number of transmitted packets (received rewards)

Reinforcement Learning, Part I
Action, reward, action-value, estimated action-value

Notations:

- The action and reward at times step t denoted in capital letters: A_t, R_t
- Their possible values are denoted in lower case : a, r



We evaluate each action with its action-value function :

- What is the expected return if we choose this channel (action)?

$$q_*(a) = \mathrm{E}[R_t | A_t = a]$$

Problem : We don't know it ☹

Reinforcement Learning, Part I
Action, reward, action-value, estimated action-value

We need to estimate the action-value function :

- Test each channel many times
- Compute an average for each channel

$$Q_t(a) = \frac{\text{sum of rewards when we took the action } a}{\text{number of time we took the action } a}$$

$$= \frac{\sum_{i=1}^{N_t(a)} R_i^a}{N_t(a)}$$

Notations:

- The true action-value function is denoted in lower case : $q_*(a)$
- Its estimate at time t is denoted in capital letters : $Q_t(a)$
- $N_t(a)$ denotes the number of times action a has been selected at time t
- $\left[R_1^a, R_2^a, \ldots, R_{N_t(a)}^a\right]$ denotes the rewards we got when taking the action a

Reinforcement Learning, Part I
Action, reward, action-value, estimated action-value

We can then choose the best action at time t :

$$A_t = \arg\max_a Q_t(a)$$

We chose the action that will most probably give the best reward

Tradeoff:

- We need to test each channel many times to have the best estimate $Q_t(a)$ → Exploration
- We need to take the best action to maximize the rewards → Exploitation

Reinforcement Learning, Part I
Policies

How to both explore and exploit ? We follow a policy π

- The policy define how we chose the action at each time step t

The most basic policy is the ϵ-greedy policy:

At each time step t:

- With a probability ϵ, take a random action

  → Refine the action-value estimation for that action

- With a probability (1- ϵ), take the best action $A_t = \arg\max_a Q_t(a)$

  → Maximize the reward

ϵ defines the tradeoff exploration/exploitation

Reinforcement Learning, Part I
Policies

Another one is the Upper-Confidence-Bound (UCB) policy:

$N_t(a)$ denotes the number of times action a has been selected at time t

Select the best action according to :

$$A_t = \arg\max_a \left[Q_t(a) + \sqrt{\frac{\ln(t)}{N_t(a)}} \right]$$

Estimate of the average return for the action a

Measure of uncertainty of the estimate $Q_t(a)$

Often takes the best action but still refine the estimate $Q_t(a)$

Let’s play ☺

Exercise

Multiple Access Channel with Reinforcement Learning

1. Reinforcement Learning, part I
    1. Multi-armed Bandits
    2. Action, reward, action-value, estimated action-value
    3. Policies
    4. Your turn ☺
2. Renforcement Learning, part II
    1. Classic RL problem and Markov Decision Process
    2. Return, state-value, action-value
    3. Temporal Difference Learning
    4. Your turn ☺
3. Deep Reinforcement Leaning
    1. Q-network
    2. Experience replay
    3. Target Network
    4. Your turn ☺

Reinforcement Learning, Part II
Classic RL problem

Problem formulation:

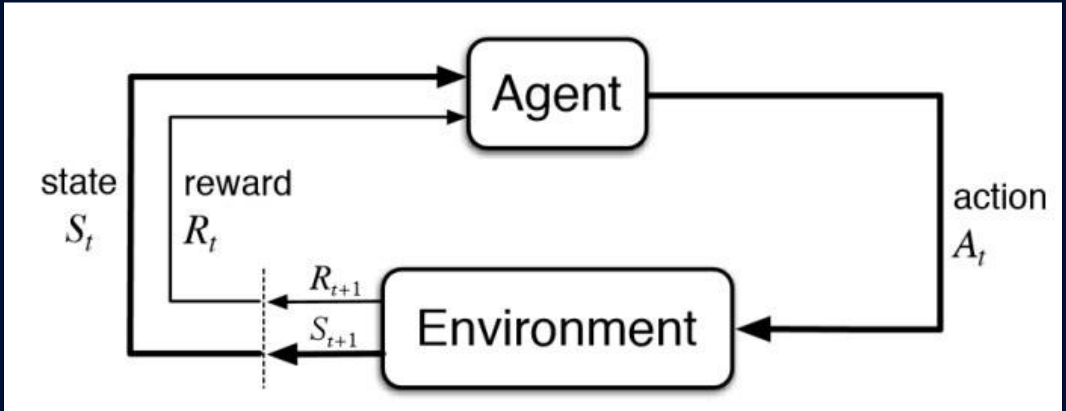
- You are in an industrial environment with 7 different channels
- All existing machines transmit with a certain periodicity
- You install a new IoT sensor, and need to find on which channel to transmit 5 packets
- You can sense the channels before sending a packet(!)

→ Which channels do you choose?

Framework: At each time step

- You sense the channels (state)
- You see if the previously transmitted packet has been correctly received (reward)
- You decide on which channel you transmit next (action)

Reinforcement Learning, Part II
Classic RL problem



The IoT sensor is a agent which interacts with an environment

At each time step t :

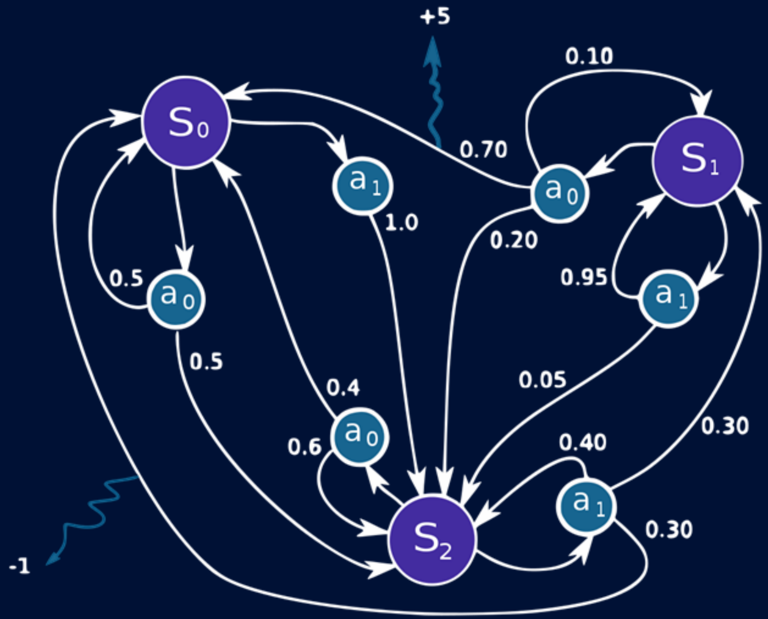
- The agent receives a state (sensed channels) and a reward (previous tx successful?)
- The agent takes an action (choose the next channel)

The sequence is defined by $S_0, A_0, \mathrm{R}_1, \mathrm{S}_1, \mathrm{A}_1, \mathrm{R}_2, \mathrm{S}_2, \mathrm{A}_2, \mathrm{R}_3, \ldots$

Reinforcement Learning, Part II
Markov Decision Process

A Markov Decision Process (MDP) is a 4-tuple $(\mathcal{S}, \mathcal{A}_s, \mathcal{P}_a, \mathcal{R}_a)$:

- $\mathcal{S}$ is a finite set of states
- $\mathcal{A}_s$ is the finite set of actions available from state s
- $\mathcal{P}_a(s, s') = \Pr(s_{t+1} = s' | s_t = s, a_t = a)$ is the probability that action a in state s at time t will lead to state s' at time $t + 1$
- $\mathcal{R}_a(s, s')$ is the reward received after transitioning from state s to state s', due to action a



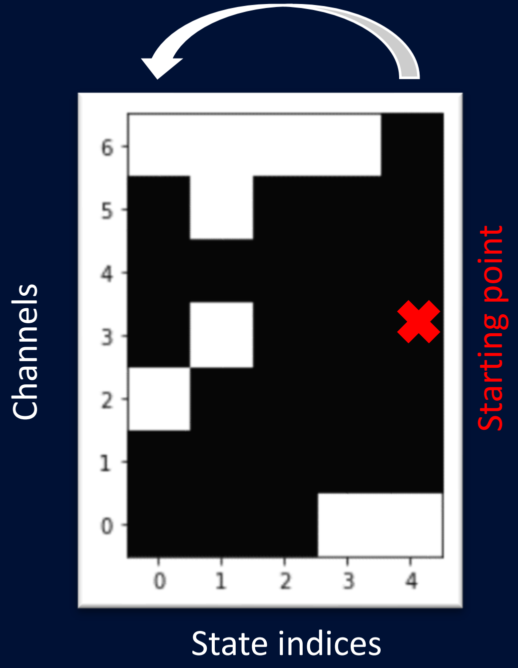
Reinforcement Learning, Part II
Classic RL problem

For simplicity, let's have a known deterministic environment:

- The white boxes are free channels
- The black boxes are already used channels
- You have 5 different channel states
- You start at the "starting point"

Goal : Find the best channels for the 5 transmissions

The transmission of 5 packets is called an episode



Reinforcement Learning, Part II
Classic RL problem

The state consists of:

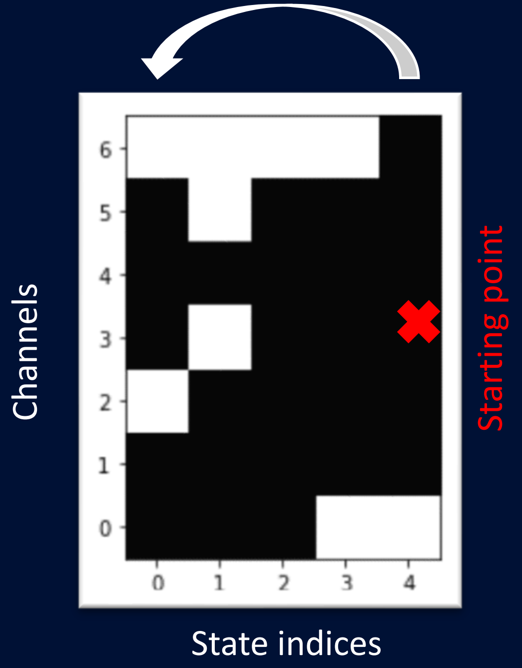
- The state index we sense (5 possibilities)
- The channel in which we transmitted (7 possibilities)
- A Boolean to indicate if we reached the last state (5 transmissions)

The rewards are :

- 1 if the transmission was successful
- 0 otherwise

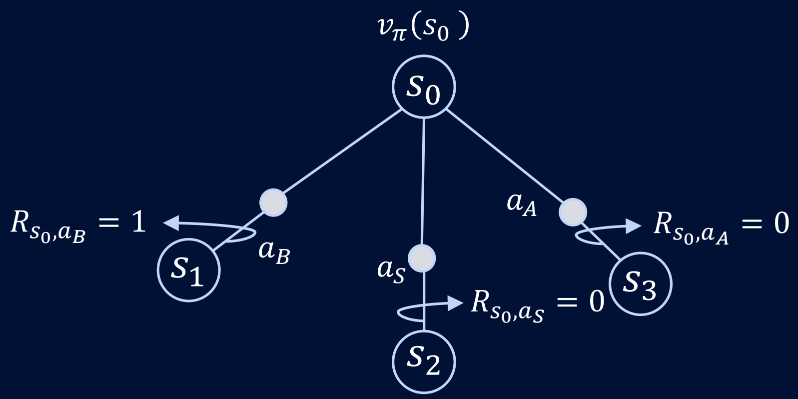
The possible actions are:

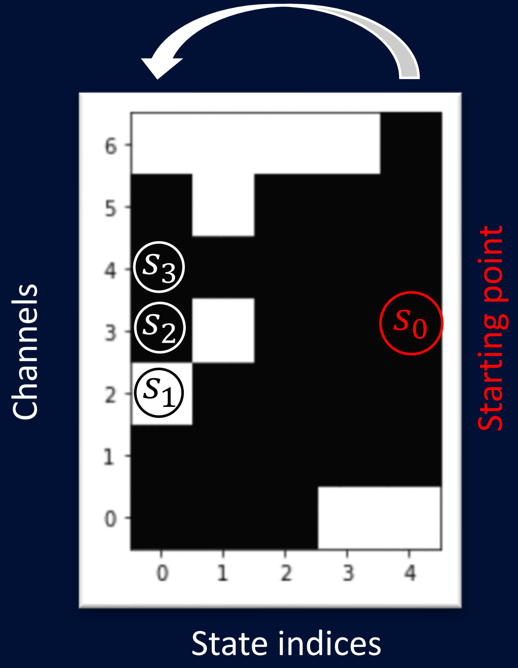
- Transmit in the channel above (mod 7) : A
- Transmit in the same channel : S
- Transmit in the channel below (mod 7) : B



Reinforcement Learning, Part II
Classic RL problem

First state : $S_0 = [state\_index, prev\_channel, bool] = [4, 3, 0]$





Possible second state : $S_1 = [0, 2, 0]$, $S_2 = [0, 3, 0]$, $S_3 = [0, 4, 0]$

Reinforcement Learning, Part II
Return, state-value, action-value

The discounted return is the sum of rewards after a time step t :

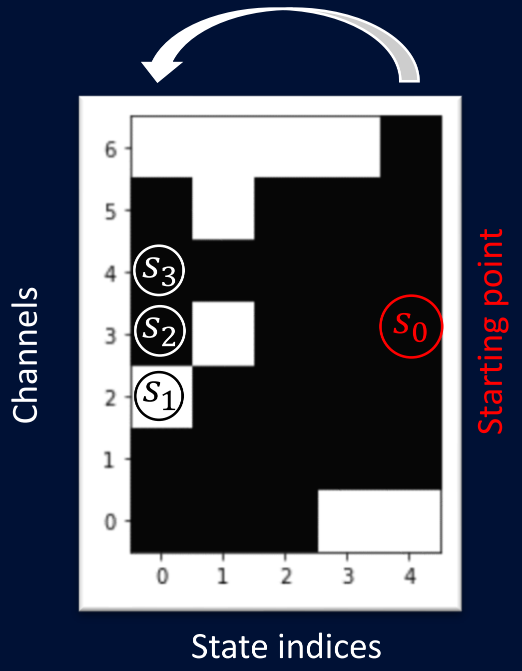
$$G_t = R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \cdots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}$$

$$= \mathrm{R}_{t+1} + \gamma \, G_{t+1}$$

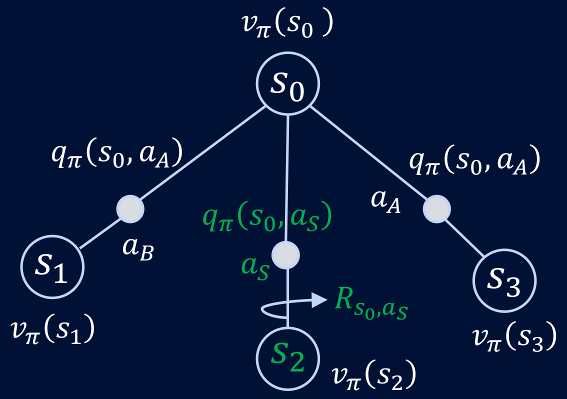
The discount factor γ , with $0 < \gamma < 1$, is used for:

- Having a finite return even if the number of future time steps k is infinite
- Maximizing short-term ($\gamma = 0$) or long-term ($\gamma = 1$) reward

Note that in our problem, the maximum time step is 5



Reinforcement Learning, Part II
Return, state-value, action-value



For a given state s :

- The policy $\pi(a|s)$ is the probability of choosing an action a
- The state-value function is the expected return

$$v_\pi(s) = \mathrm{E}[G_t(\pi)|\, S_t = s]$$

- The action-value function is the expected return if we choose action a

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

We want to find a policy that choose the best actions according to the $q_\pi(s, a_i)$

But how do we estimate those $q_\pi(s, a_i)$?

Reinforcement Learning, Part II
Return, state-value, action-value

The optimal policy is the one that maximizes $v_\pi(s)$ and $q_\pi(s)$:

- The optimal action-value function is

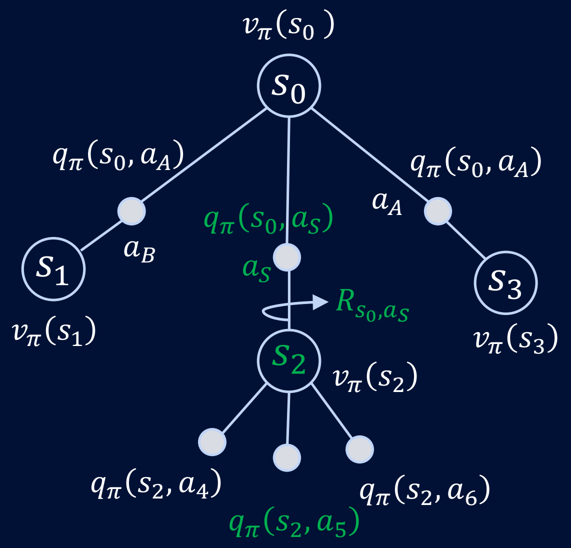
$$q_*(s,a) = \max_\pi q_\pi(s,a)$$

- The optimal state-value function is

$$\begin{aligned} v_*(s) &= \max_\pi v_\pi(s) \\ &= \max_a q_*(s,a) \end{aligned}$$

Bellman optimality equation :

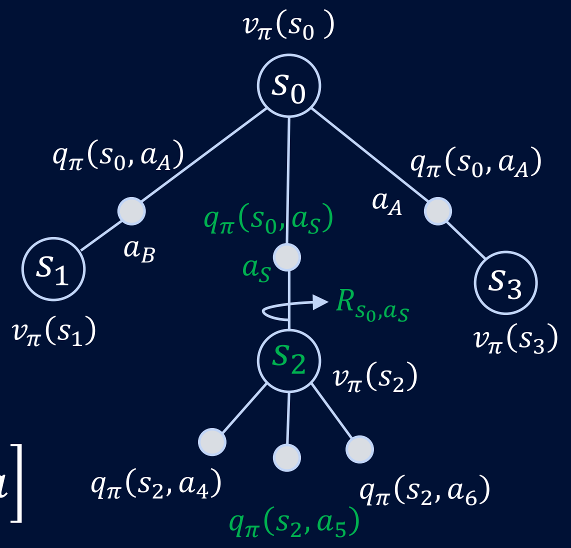
$$\begin{aligned} q_*(s,a) &= \max_\pi \mathrm{E}[G_t(\pi) |\, S_t = s, A_t = a] \\ &= \max_\pi \mathrm{E}[\mathrm{R}_{t+1} + \gamma G_{t+1}(\pi) |\, S_t = s, A_t = a] \\ &= \mathrm{E}[\mathrm{R}_{t+1} + \gamma v_*(S_{t+1}) |\, S_t = s, A_t = a] \\ &= \mathrm{E}\left[\mathrm{R}_{t+1} + \gamma \max_{a'} q_*(S_{t+1}, a') |\, S_t = s, A_t = a\right] \end{aligned}$$



Reinforcement Learning, Part II
Return, state-value, action-value

Bellman optimality equation

Trick : when the latest reward is received, there is no more state
“End” Boolean ξ: 1 if we reached the last state, 0 otherwise

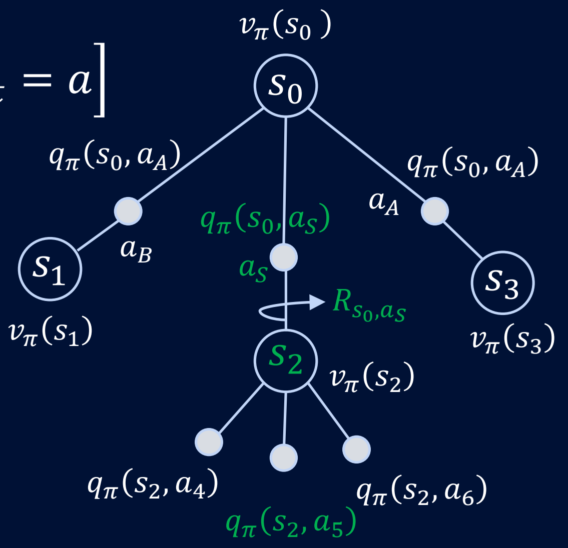


$$q_*(s,a) = \mathrm{E}\left[\mathrm{R}_{t+1} + \gamma(1-\xi)\max_{a'} q_*(S_{t+1}, a') \middle| S_t = s, A_t = a\right]$$

Next goal : find an estimate $Q_*(s,a)$ of $q_*(s,a)$

Reinforcement Learning, Part II
Temporal Difference Learning

Estimate $q_*(s,a) = \mathrm{E}\left[\mathrm{R}_{t+1} + \gamma(1-\xi)\max_{a'} q_*(S_{t+1},a')|S_t = s, A_t = a\right]$



Q-Learning : wait to finish a $S_t, A_t, R_{t+1}, S_{t+1}$ (with a policy π)

(0. Initialize all $\mathrm{Q}_*(s,a)$ randomly)

1. Take the $\mathrm{Q}_*(S_t,A_t)$ associated with your state and action
2. When in S_{t+1}, take the best q-value: $\max_a Q_*(S_{t+1},a)$
3. Compute a better estimate $Q'_*(S_t,A_t) = R_{t+1} + \gamma(1-\xi)\max_a Q_*(S_{t+1},a)$
4. Compute an error $Q'_*(S_t,A_t) - Q_*(S_t,A_t)$
5. Update $\mathrm{Q}_*(S_t,A_t) \leftarrow Q_*(S_t,A_t) + \alpha\,[Q'_*(S_t,A_t) - Q_*(S_t,A_t)]$

α is the learning rate

Temporal Difference (TD): use the time step t+1 to refine the time step t

Reinforcement Learning, Part II
Temporal Difference Learning

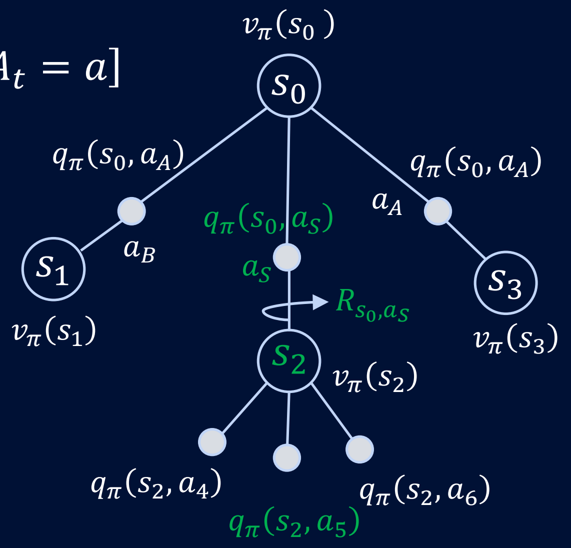
With a policy π: $q_\pi(s,a) = \mathrm{E}[\mathrm{R}_{t+1} + \gamma(1-\xi)q_\pi(S_{t+1},A_{t+1}) | \, S_t = s, A_t = a]$

SARSA : wait to finish a $S_t, A_t, R_{t+1}, S_{t+1}, A_{t+1}$

(0. Initialize all $\mathrm{Q}(s,a)$ randomly)

1. Take the $\mathrm{Q}_\pi(S_t, A_t)$ associated with your state and action
2. Compute a better estimate $Q'_\pi(S_t,A_t) = R_{t+1} + \gamma(1-\xi)Q_\pi(S_{t+1},A_{t+1})$
3. Compute an error $Q'_\pi(S_t,A_t) - Q_\pi(S_t,A_t)$
4. Update $\mathrm{Q}_\pi(S_t,A_t) \leftarrow Q_\pi(S_t,A_t) + \alpha\,[Q'_\pi(S_t,A_t) - Q_\pi(S_t,A_t)]$

α is the learning rate



Here we estimated the $q_\pi(s,a)$ according to another policy π

Reinforcement Learning, Part II
Temporal Difference Learning

With a policy π, record $S_t, A_t, R_{t+1}, S_{t+1}, A_{t+1}$

- SARSA: On-policy method

$$Q_\pi(S_t, A_t) \leftarrow Q_\pi(S_t, A_t) + \alpha[R_{t+1} + \gamma(1-\xi)Q_\pi(S_{t+1}, A_{t+1}) \; - Q_\pi(S_t, A_t)]$$

Behavior policy
i.e., ϵ-greedy

Behavior policy
i.e., ϵ-greedy

You estimate the Q_π according to the policy you are using

- Q-Learning : Off-policy method

$$Q_*(S_t, A_t) \leftarrow Q_*(S_t, A_t) + \alpha\left[R_{t+1} + \gamma(1-\xi)\max_a Q_*(S_{t+1}, a) - Q_*(S_t, A_t)\right]$$

Optimal policy

Optimal policy

You use the policy π to explore and estimate the optimal policy

Reinforcement Learning, Part II
Classic RL problem

The state comprises both:

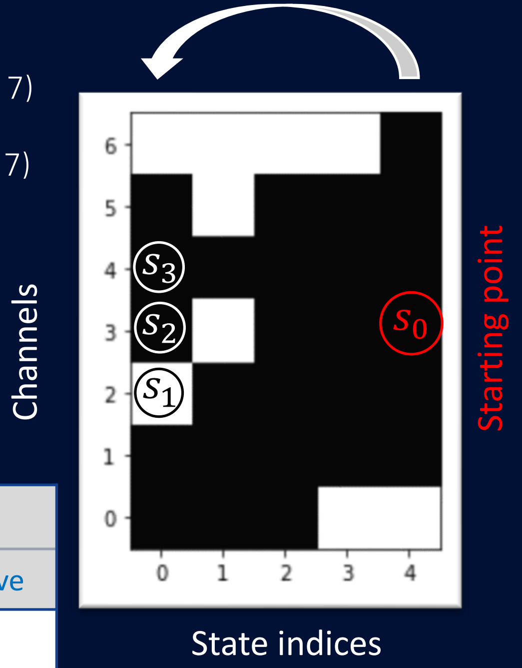
- The channel in which we transmitted (7 possibilities)
- The channel state index we sense (5 possibilities)
- The ξ Boolean (=1 if it's the end, =0 otherwise)

The possible actions are :

- Tx in channel above (mod 7)
- Tx in same chanel
- Tx in channel below (mod 7)

The rewards are :

- 1 if the transmission was successful
- 0 otherwise



Q-Learning : fill the Q-table following a ϵ-greedy policy

	State index 0			...	State index 4		
	a_B: Below	a_S : Same	a_A : Above	...	a_B: Below	a_S : Stay	a_A : Above
...	...	...	...	...	...	...	...
Ch 3	$Q_*([3,0],a_B)$	$Q_*([3,0],a_S)$	$Q_*([3,0],a_A)$	...	$Q_*([3,4],a_B)$	$Q_*([3,4],a_S)$	$Q_*([3,4],a_A)$
...	...	...	...	...	...	...	...

Let’s play ☺

Exercise

Multiple Access Channel with Reinforcement Learning

1. Reinforcement Learning, part I
    1. Multi-armed Bandits
    2. Action, reward, action-value, estimated action-value
    3. Policies
    4. Your turn ☺
2. Renforcement Learning, part II
    1. Classic RL problem and Markov Decision Process
    2. Return, state-value, action-value
    3. Temporal Difference Learning
    4. Your turn ☺
3. Deep Reinforcement Leaning
    1. Q-network
    2. Experience replay
    3. Target Network
    4. Your turn ☺

Deep Reinforcement Learning
Q-Network

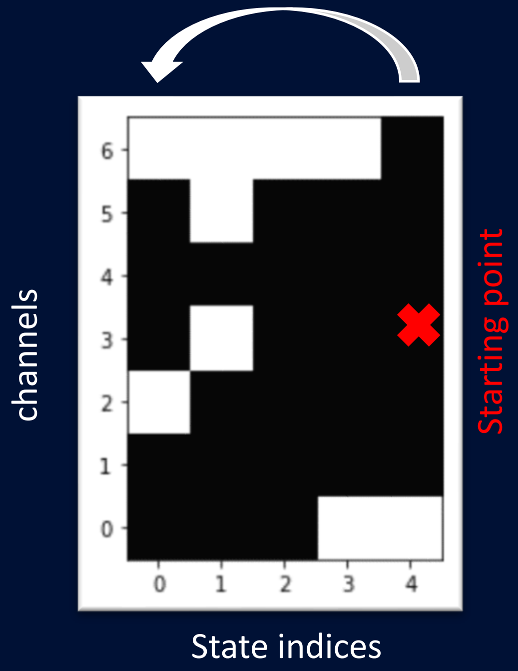
Previously, we knew that there were only 5 channel states
→ What if we don't know that?

One state is now defined by the state vector :

Channel state | Current channel

0	0	0	0	0	0	1	0	0	0	1	0	0	0

Free channels are set to 1 | The channel we are in is set to 1

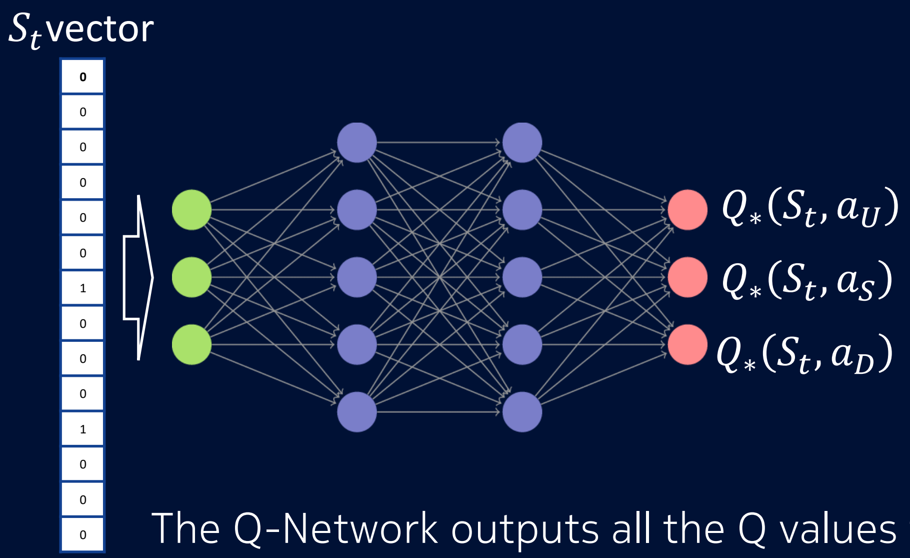


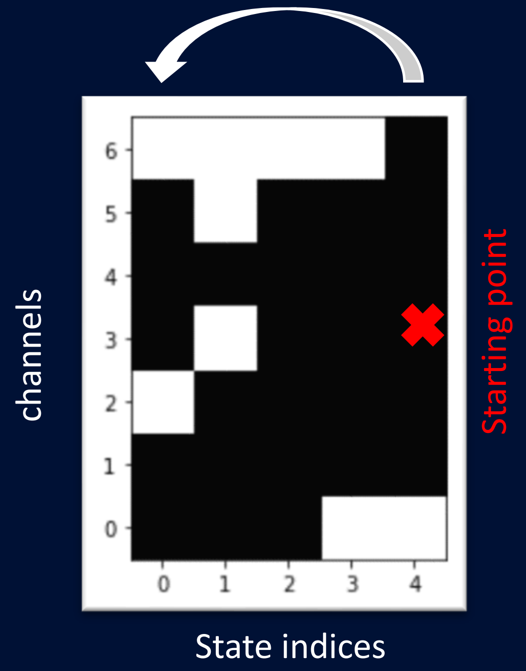
And the ξ boolean

Deep Reinforcement Learning
Q-Network

We don't want to store a huge Q-table.

We can use a Q-Network instead :

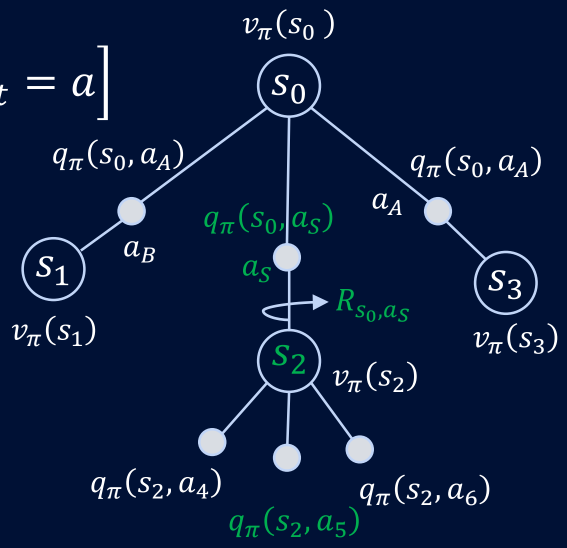




The Q-Network outputs all the Q values for a given states

Deep Reinforcement Learning
Q-Network

Estimate $q_*(s,a) = \mathrm{E}\left[\mathrm{R}_{t+1} + \gamma(1-\xi)\max_{a'} q_*(S_{t+1},a')|S_t = s, A_t = a\right]$



Q-Learning : wait to finish a $S_t, A_t, R_{t+1}, S_{t+1}$

(0. Initialize all $\mathrm{Q}_*(s,a)$ randomly)

1. Take the $\mathrm{Q}_*(S_t,A_t)$ associated with your state and action
2. When in S_{t+1}, take the best q-value : $\max_a Q_*(S_{t+1},a)$
3. Compute a better estimate $Q'_*(S_t,A_t) = R_{t+1} + \gamma \max_a Q_*(S_{t+1},a)$
4. Compute loss : $\mathrm{MSE}\left(Q'_*(S_t,A_t),\ \ Q_*(S_t,A_t)\right)$
5. Update parameters of the Q-Network by SGD to minimize the loss

Deep Reinforcement Learning
Q-Network

$$loss = MSE\left(\overbrace{R_{t+1} + \gamma(1-\xi)\max_a Q_*(S_{t+1}, a)}^{\text{Target}} - \overbrace{Q_*(S_t, A_t)}^{\text{Prediction}}\right)$$

Each time we update for one prediction, every parameters in the NN changes!
Two problems arises :

- *Correlation* : when you follow the trajectory, your NN will be optimized only for the last few (s, a) that you took
- *Nonstationary target* : each time we update the NN, the target change as well
→ not stable

Deep Reinforcement Learning
Experience Replay

To remove *correlation*, we store all experiences $(S_t, A_t, R_{t+1}, S_{t+1})$ in a dataset.

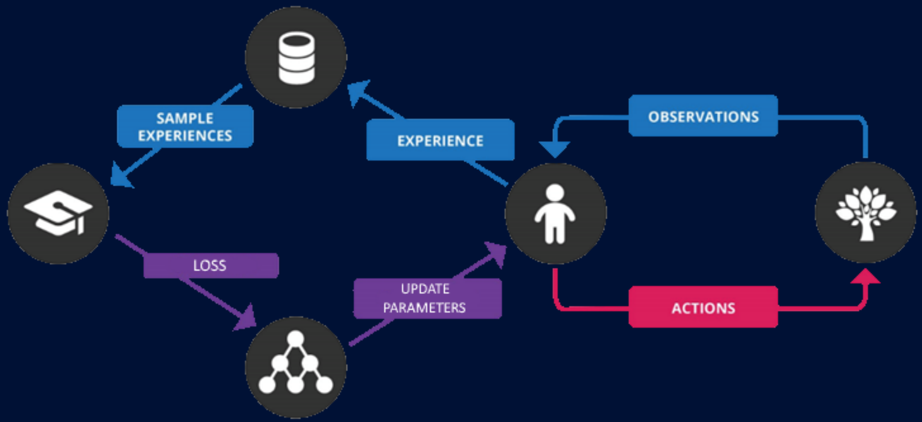
Then, at each iteration, we perform experience replay:

- We take a random batch of experiences
- We compute the predictions and targets
- We evaluate the loss and update the Q-Network

$$loss = MSE(\text{predictions}, \text{targets})$$

Circular buffer (FIFO)

S_1, A_1, R_2, S_2
S_2, A_2, R_3, S_3
S_3, A_3, R_4, S_4
S_4, A_4, R_5, S_5
…

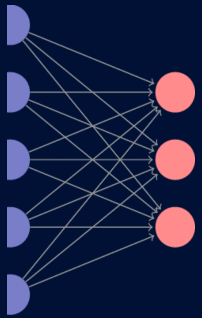


Deep Reinforcement Learning
Experience Replay

To remove *correlation*, we store all samples $(S_t, A_t, R_{t+1}, S_{t+1})$ in a dataset.

$$loss = MSE(\text{predictions}, \text{targets})$$

The targets can only reflect the action chosen in the sample
If at state S_t, the action taken was a_A:

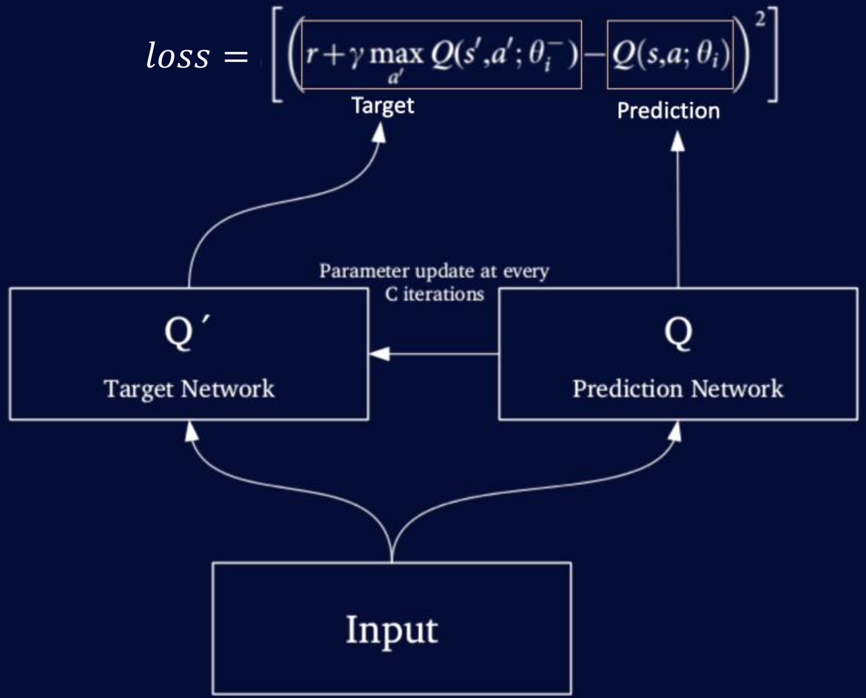


$$MSE\begin{bmatrix} \overbrace{Q_*(S_t, a_A)}^{\text{Prediction}} - \overbrace{R_{t+1} + \gamma(1-\xi)\max_a Q_*(S_{t+1}, a)}^{\text{Target}} \\ Q_*(S_t, a_S) - Q_*(S_t, a_s) \\ Q_*(S_t, a_B) - Q_*(S_t, a_D) \end{bmatrix} = MSE\begin{bmatrix} pred - target \\ 0 \\ 0 \end{bmatrix}$$

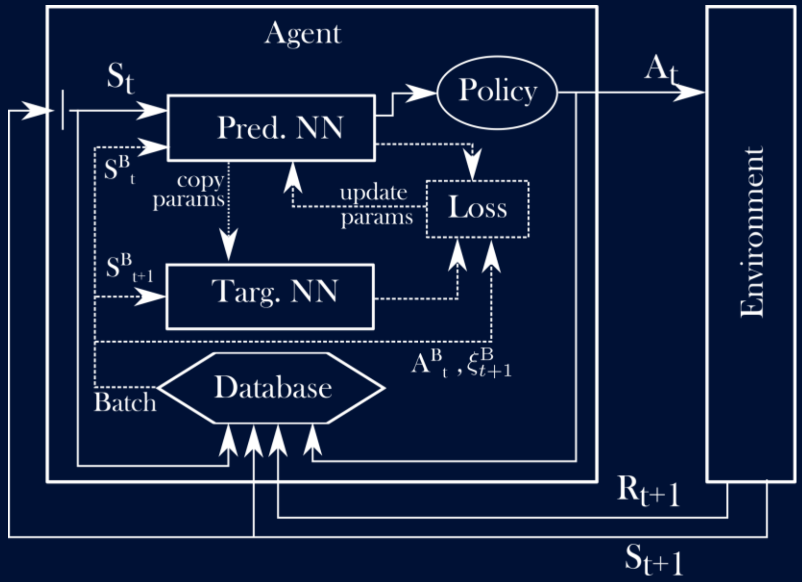
Deep Reinforcement Learning
Target Network

To alleviate the *nonstationary target*, we maintain a target Q-Network :

- The targets are computed according to the target network
- The parameters of the target network are updated every C iterations



Deep Reinforcement Learning
Target Network



Main algorithm :

Initialize the pred.NN and the targ.NN with the same params

Play actions according to a policy π to populate the datasets

For a given number of episodes :

- While $\xi \neq 1$:
  - Choose an action A_t according to the state S_t and the policy π
  - Receive R_{t+1}, S_{t+1} and store $(A_t, S_t, R_{t+1}, S_{t+1})$ in the database
  - Take a random batch from the database (B = batch size)
  - Compute the loss using targets from the target network
  - Update the (prediction) Q-Network
- Every C iterations, copy the parameters of the pred.NN to the targ.NN

Let’s play ☺

Exercise

Multiple Access Channel with Reinforcement Learning

Thank you

Everything is available on
mgoutay.github.io