

An Introduction to Reinforcement Learning

From theory to algorithms

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Foreword

As of Fall 2023, this document contains lecture notes from a course given in Master 2 in *Université Paris-Saclay*. These are highly incomplete and constantly updated as the lectures are given.

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Introduction

Reinforcement learning deals with problems where an agent sequentially interacts with a dynamic environment, which yields a sequence of rewards. We aim at finding the decision rule for the agent which yields the highest cumulative reward. We first study the case where characteristics of the environments are known, and then turn to techniques for dealing with unknown environments, which must then be progressively learnt through repeated interaction.

Reinforcement learning achieves great success in various applications: super-human algorithm for Go, robotics, finance, protein structure prediction, to name a few. Because it is so successful in practice, many resources are practice-oriented.

In these lectures, we first aim at a very rigorous presentation of the basic notions and tools. These building blocks will then be used to define algorithms, and establish theoretical guarantees for some of them.

Chapter 1

Markov decision processes

The framework for reinforcement learning is the Markov Decision process, which is a repeated interaction between an agent and a dynamic environment, which can be informally described as follows.

We are given three finite nonempty sets \mathcal{S} , \mathcal{A} and $\mathcal{R} \subset \mathbb{R}$. The environment chooses an initial *state* $S_0 \in \mathcal{S}$ and reveals it to the agent. The agent then chooses an *action* $A_0 \in \mathcal{A}$, possibly at random. The environment then draws $(R_1, S_1) \in \mathcal{R} \times \mathcal{S}$ according to a probability distribution that depends on S_0 and A_0 . The *reward* R_1 and the new state S_1 are revealed to the agent. The agent then chooses $A_2 \in \mathcal{A}$, possibly at random. The environment then draws $(R_2, S_2) \in \mathcal{R} \times \mathcal{S}$ according to a probability distribution which depends on S_0 and A_0 , and so on.

The total reward of the agent $\sum_{t=1}^{+\infty} \gamma^{t-1} R_t$, where $0 < \gamma < 1$ is a given *discount factor*. The goal is to find the decision rule for the agent that yields the highest expected total reward.

Note that at stage $t \geq 1$, the choice of actions A_t by the agent may depend on all previously observed information, meaning $(S_0, A_0, R_1, \dots, R_t, S_t)$.

Depending on the problem, the dynamics of the environment (which maps a state-action pair to a probability distribution over reward-state pairs) may be known or not.

This chapter presents basic notions regarding MDPs, in a formal fashion.

For a finite set I , we denote $\Delta(I)$ the corresponding unit simplex in \mathbb{R}^I :

$$\Delta(I) = \left\{ x \in \mathbb{R}_+^I, \sum_{i \in I} x_i = 1 \right\}$$

and interpret it as set the probability distributions over I . For $i \in I$, the corresponding Dirac measure is denoted δ_i .

1.1 Formal definition

Definition 1.1.1. A *finite Markov Decision Process* (MDP) is a 4-tuple $(\mathcal{S}, \mathcal{A}, \mathcal{R}, p)$ where $\mathcal{S}, \mathcal{A}, \mathcal{R}$ are nonempty finite sets and $p : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \times \mathcal{R} \rightarrow [0, 1]$ is such that for all $s, a \in \mathcal{S} \times \mathcal{A}$,

$$\sum_{(r, s') \in \mathcal{R} \times \mathcal{S}} p(s, a, r, s') = 1.$$

The elements of \mathcal{S} , \mathcal{A} and \mathcal{R} are respectively called *states*, *actions* and *rewards*. The following notation will be used:

$$p(r, s' | s, a) = p(s, a, r, s'), \quad (s, a, r, s') \in \mathcal{S} \times \mathcal{A} \times \mathcal{R} \times \mathcal{S}.$$

The knowledge of \mathcal{S} and \mathcal{A} is always assumed, but \mathcal{R} and p may not be known, depending on the context.

From now on, we assume that a finite MDP is given.

Remark 1.1.2. For fixed values $(s, a) \in \mathcal{S} \times \mathcal{A}$, $p(s, a, \cdot)$ defines a probability distribution on $\mathcal{R} \times \mathcal{S}$, which justifies notation $p(\cdot | s, a)$.

Definition 1.1.3. Let $t \geq 1$. A *history of length t* is a finite sequence of the form

$$(s_0, a_0, r_1, s_1, a_1, r_2, s_2, a_2, \dots, s_{t-1}, a_{t-1}, r_t, s_t) \in (\mathcal{S} \times \mathcal{A} \times \mathcal{R})^t \times \mathcal{S}.$$

By convention, a history of length 0 is an element $s_0 \in \mathcal{S}$. $\mathcal{H}^{(t)}$ denotes the set of histories of length t and $\mathcal{H}^\infty = (\mathcal{S} \times \mathcal{A} \times \mathcal{R})^\mathbb{N}$ the set of infinite histories.

Remark 1.1.4. Histories of length t correspond to the information observed by the agent at step t before choosing its action.

1.2 Policies

We now define policies, which are the formalization of decision rules for the agent. We first consider general policies, which allow for random decisions, as well as decision rules that depend on all available information (from the beginning of the interaction to the present state).

Definition 1.2.1. A *policy* is a sequence of maps $\pi = (\pi_t)_{t \geq 0}$ where $\pi_t : \mathcal{H}^{(t)} \rightarrow \Delta(\mathcal{A})$. For each $t \geq 0$ and $h^{(t)} \in \mathcal{H}^{(t)}$, denote

$$\pi_t(a | h^{(t)}) := \pi_t(h^{(t)})_a.$$

Π denotes the set of all policies.

Definition 1.2.2. A policy $\pi = (\pi_t)_{t \geq 0}$ is

- *deterministic* if for each $t \geq 0$ and $h^{(t)} \in \mathcal{H}^{(t)}$, there exists $a \in \mathcal{A}$ such that $\pi_t(h^{(t)})$ is the Dirac distribution in a ;
- *Markovian* if for each $t \geq 0$, π_t is constant in all its variables but the last: in other words for a fixed value $s_t \in \mathcal{S}$, the map $\pi_t(\cdot, s_t)$ is constant; π_t can then be represented as $\pi_t : \mathcal{S} \rightarrow \Delta(\mathcal{A})$;
- *stationary* if it is Markovian and if for all $t \geq 0$, $\pi_t = \pi_0$; π can then be represented as $\pi : \mathcal{S} \rightarrow \Delta(\mathcal{A})$ and denoted $\pi(a|s) = \pi(s)_a$ for $(s, a) \in \mathcal{S} \times \mathcal{A}$.

Denote Π_0 (resp. $\Pi_{0,d}$) the set of stationary policies (resp. stationary and deterministic policies). A stationary and deterministic policy can be represented as $\pi : \mathcal{S} \rightarrow \mathcal{A}$.

In the next chapter, we will establish that there exists a stationary and deterministic optimal policy, and focus on stationary policies. We will however continue working with non-deterministic strategies, as they will later prove handy for *exploring* an unknown environment.

1.3 Induced probability distributions over histories

As soon as an MDP, a policy π , and an initial state distribution μ are given, the interaction produces random variables $S_0, A_0, R_1, S_1, A_0, R_2, \dots$. This is formalized by the proposition below.

We first introduce the following notation. For $T \geq 0$ and $h^{(T)} = (s_0, a_0, r_1, \dots, r_T, s_T)$, we consider the following associated subset of \mathcal{H}^∞ :

$$\text{Cyl } h^{(T)} = \{s_0\} \times \{a_0\} \times \{r_1\} \times \dots \times \{r_T\} \times \{s_T\} \times (\mathcal{A} \times \mathcal{R} \times \mathcal{S})^\mathbb{N}.$$

Proposition 1.3.1. *Let $\mu \in \Delta(\mathcal{S})$ and a policy π . There exists a unique probability measure $\mathbb{P}_{\mu,\pi}$ on $\mathcal{H}^\infty = (\mathcal{S} \times \mathcal{A} \times \mathcal{R})^\mathbb{N}$ (equipped with the product σ -algebra) such that for all $T \geq 0$, and all $h^{(T)} = (s_0, a_0, r_1, \dots, r_T, s_T) \in \mathcal{H}^{(T)}$,*

$$\mathbb{P}_{\mu,\pi}(\text{Cyl } h^{(T)}) = \mu(s_0) \prod_{t=0}^{T-1} \pi_t(a_t | h^{(t)}) p(r_{t+1}, s_{t+1} | s_t, a_t).$$

where for each $0 \leq t \leq T$, $h^{(t)} = (s_0, a_0, r_1, \dots, s_{t-1}, a_{t-1}, r_t, s_t)$.

Sketch of proof. The above expression defines a value for each set of the form $\text{Cyl } h^{(T)}$ for $T \geq 0$ and $h^{(T)} \in \mathcal{H}^{(T)}$. The map $\mathbb{P}_{\mu,\pi}$ can then be extended to so-called cylinder sets of the form

$$\prod_{t=0}^T (\mathcal{S}_t \times \mathcal{A}_t \times \mathcal{R}_{t+1}) \times \mathcal{S}_{T+1} \times (\mathcal{A} \times \mathcal{R} \times \mathcal{S})^\mathbb{N},$$

where $\mathcal{S}_0, \dots, \mathcal{S}_{T+1} \subset \mathcal{S}$, $\mathcal{A}_0, \dots, \mathcal{A}_T \subset \mathcal{A}$ and $\mathcal{R}_1, \dots, \mathcal{R}_{T+1} \subset \mathcal{R}$ by summing as follows:

$$\begin{aligned} \mathbb{P}_{\mu, \pi} & \left(\prod_{t=0}^T (\mathcal{S}_t \times \mathcal{A}_t \times \mathcal{R}_{t+1}) \times \mathcal{S}_{T+1} \times (\mathcal{A} \times \mathcal{R} \times \mathcal{S})^{\mathbb{N}} \right) \\ &= \sum_{\substack{s_0 \in \mathcal{S}_0 \\ \vdots \\ s_{T+1} \in \mathcal{S}_{T+1}}} \sum_{\substack{a_0 \in \mathcal{A}_0 \\ \vdots \\ a_T \in \mathcal{A}_T}} \sum_{\substack{r_1 \in \mathcal{R}_1 \\ \vdots \\ r_{T+1} \in \mathcal{R}_{T+1}}} \mu(s_0) \prod_{t=0}^T \pi_t(a_t | h^{(t)}) p(s_{t+1}, r_{t+1} | s_t, a_t). \end{aligned}$$

$\mathbb{P}_{\mu, \pi}$ can then be seen to satisfy the assumptions of Kolmogorov's extension theorem which assures that $\mathbb{P}_{\mu, \pi}$ can be extended to a unique probability measure on \mathcal{H}^∞ . \square

Definition 1.3.2. Let $\mu \in \Delta(\mathcal{S})$, $\pi \in \Pi$, $s \in \mathcal{S}$ and $a \in \mathcal{A}$.

- (i) $\mathbb{P}_{\mu, \pi}$ is called the *probability distribution over histories* induced by initial state distribution μ and policy π .
- (ii) We write $\mathbb{P}_{s, \pi}$ instead of $\mathbb{P}_{\delta_s, \pi}$, which is called the probability distribution over histories induced by initial state s and policy π .
- (iii) Let $\pi' = (\pi'_t)_{t \geq 0}$ defined as

$$\begin{aligned} \pi'_0(s) &= \delta_a, \\ \pi'_0(s') &= \pi_0(s') \quad \text{for } s' \neq s \\ \pi'_t &= \pi_t \quad \text{for } t \geq 1. \end{aligned}$$

$\mathbb{P}_{s, \pi'}$ is then called the probability distribution induced by initial state s , initial action a , and policy π , and is denoted $\mathbb{P}_{s, a, \pi}$.

The following shorthands will be used:

$$\begin{aligned} \mathbb{E}_{\mu, \pi} [\cdot] &= \mathbb{E}_{(S_0, A_0, R_1, \dots) \sim \mathbb{P}_{\mu, \pi}} [\cdot] \\ \mathbb{E}_{s, \pi} [\cdot] &= \mathbb{E}_{(S_0, A_0, R_1, \dots) \sim \mathbb{P}_{s, \pi}} [\cdot] \\ \mathbb{E}_{s, a, \pi} [\cdot] &= \mathbb{E}_{(S_0, A_0, R_1, \dots) \sim \mathbb{P}_{s, a, \pi}} [\cdot]. \end{aligned}$$

$\mathbb{P}_{s, a, \pi}$ corresponds to the interaction where the initial state is s , initial action is a (deterministically), and decision rule is given π only for $t \geq 1$. It cannot be defined as $\mathbb{P}_{s, a}$ conditioned on the event $A_0 = a$ because the probability $\pi(a|s)$ of this event may be zero.

Proposition 1.3.3. Let $\pi = (\pi_t)_{t \geq 0}$ be a policy and $s \in \mathcal{S}$. Then,

$$\mathbb{P}_{s, \pi} = \sum_{a \in \mathcal{A}} \pi_0(a|s) \cdot \mathbb{P}_{s, a, \pi}.$$

Proof. It is sufficient to prove the identity between those two measures on the sets that appear in the statement of Proposition 1.3.1, because they would then uniquely extend to all measurable subsets of \mathcal{H}^∞ .

Let $T \geq 0$ and $h^{(T)} = (s_0, a_0, r_1, \dots, r_T, s_T) \in \mathcal{H}^{(T)}$, and denote $h^{(t)} := (s_0, a_0, r_1, \dots, r_t, s_t)$ for $0 \leq t \leq T$. If $s_0 \neq s$, then the measures of the identity are zero when evaluated at $\text{Cyl } h^{(T)}$. We now assume $s_0 = s$.

Fix $a \in \mathcal{A}$ and consider π' defined as in Definition 1.3.2. Then,

$$\begin{aligned} \pi_0(a|s) \cdot \mathbb{P}_{s,a,\pi} \left(\text{Cyl } h^{(T)} \right) &= \pi_0(a|s) \prod_{t=0}^{T-1} \pi'_t(a_t|h^{(t)}) p(r_{t+1}, s_{t+1}|s_t, a_t) \\ &= \mathbb{1} \{s_0 = s\} \prod_{t=0}^{T-1} \pi_t(a_t|h^{(t)}) p(r_{t+1}, s_{t+1}|s_t, a_t) \\ &= \mathbb{1} \{a_0 = a\} \cdot \mathbb{P}_{s,\pi} \left(\text{Cyl } h^{(T)} \right). \end{aligned}$$

Summing over $a \in \mathcal{A}$ then gives

$$\sum_{a \in \mathcal{A}} \pi_0(a|s) \cdot \mathbb{P}_{s,a,\pi} \left(\text{Cyl } h^{(T)} \right) = \mathbb{P}_{s,\pi} \left(\text{Cyl } h^{(T)} \right).$$

□

Proposition 1.3.4. *Let $s \in \mathcal{S}$, $a \in \mathcal{A}$, π a stationary policy, $f : \mathcal{H}^\infty \rightarrow \mathbb{R}$ a bounded measurable function (with respect to the product σ -algebra) and random variables $(S'_0, A'_0, R'_1, S'_2, A'_2, R'_2, \dots)$ with distribution $\mathbb{P}_{s,\pi}$ or $\mathbb{P}_{s,a,\pi}$. Then, almost-surely,*

(i) For all $t \geq 0$,

$$\mathbb{E}_{S'_t, \pi} [f(S_0, A_0, R_1, \dots)] = \mathbb{E} [f(S'_t, A'_t, R'_{t+1}, \dots) \mid S'_t],$$

(ii) and for all $t \geq 1$,

$$\mathbb{E}_{S'_t, A'_t, \pi} [f(S_0, A_0, R_1, \dots)] = \mathbb{E} [f(S'_t, A'_t, R'_{t+1}, \dots) \mid S'_t, A'_t].$$

1.4 Value functions

We now introduce value functions which are fundamental tools for solving MDPs. The *optimal* value function, defined in the next chapter, associates to each state the best possible average reward than can be obtained starting from that state. Almost all algorithms aim at getting close to the optimal value function through iterative updates.

Definition 1.4.1. (i) A *state-value function* (aka *V-function*) is a function $v : \mathcal{S} \rightarrow \mathbb{R}$ or equivalently a vector $v = (v(s))_{s \in \mathcal{S}} \in \mathbb{R}^{\mathcal{S}}$.

- (ii) An *action-value function* (aka *Q-function*) is a function $q : \mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$ or equivalently a vector $q = (q(s, a))_{(s,a) \in \mathcal{S} \times \mathcal{A}} \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$.

We equip both spaces with the ℓ^∞ norm:

$$\|v\|_\infty = \max_{s \in \mathcal{S}} |v(s)|, \quad \|q\|_\infty = \max_{(s,a) \in \mathcal{S} \times \mathcal{A}} |q(s, a)|,$$

and with component-wise inequalities:

$$v \leq v' \iff \forall s \in \mathcal{S}, v(s) \leq v'(s),$$

$$q \leq q' \iff \forall (s, a) \in \mathcal{S} \times \mathcal{A}, q(s, a) \leq q'(s, a).$$

Lemma 1.4.2. *Let $(R_t)_{t \geq 1}$ be a sequence of random variables with values in \mathcal{R} and $\gamma \in (0, 1)$. Then, the series $\sum_{t \geq 1} \gamma^{t-1} R_t$ converges almost-surely, and its sum is integrable.*

Proof. \mathcal{R} being a finite subset of \mathbb{R} , it holds that $\max_{r \in \mathcal{R}} |r| < +\infty$. Then,

$$|\gamma^{t-1} R_t| \leq \gamma^{t-1} \max_{r \in \mathcal{R}} |r|, \quad \text{a.s.}$$

The result follows the dominated convergence theorem. \square

Definition 1.4.3. Let $\pi \in \Pi$ and $\gamma \in (0, 1)$.

- (i) The *state-value function of policy π* with discount factor γ is defined as

$$v_\pi^{(\gamma)}(s) = \mathbb{E}_{s, \pi} \left[\sum_{t=1}^{+\infty} \gamma^{t-1} R_t \right], \quad s \in \mathcal{S}.$$

- (ii) The *action-value function of policy π* with discount factor γ is defined as

$$q_\pi^{(\gamma)}(s, a) = \mathbb{E}_{s, a, \pi} \left[\sum_{t=1}^{+\infty} \gamma^{t-1} R_t \right], \quad (s, a) \in \mathcal{S} \times \mathcal{A}.$$

We may denote $v_\pi = v_\pi^{(\gamma)}$ and $q_\pi = q_\pi^{(\gamma)}$ when γ is clear from the context.

Remark 1.4.4. $v_\pi(s)$ corresponds to the expected total reward starting from state s and following policy π .

Chapter 2

Bellman operators & optimality

Bellman operators are the fundamental tool for solving MDPs. This chapter introduces their definitions and properties. We then define optimal value functions and policies, and characterize them with the help of the Bellman operators.

We assume that $\gamma \in (0, 1)$ is given. The image of an element $x \in X$ by a map $F : X \rightarrow Y$ will often be denoted Fx instead of $F(x)$.

2.1 Bellman operators

Definition 2.1.1. Let π be a stationary policy. We define the following operators.

(i) $D^{(\gamma)} : \mathbb{R}^{\mathcal{S}} \rightarrow \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ as

$$(D^{(\gamma)}v)(s, a) = \sum_{(r, s') \in \mathcal{S} \times \mathcal{R}} p(r, s' | s, a)(r + \gamma v(s')), \quad s \in \mathcal{S}, a \in \mathcal{A}.$$

(ii) $E_\pi : \mathbb{R}^{\mathcal{S} \times \mathcal{A}} \rightarrow \mathbb{R}^{\mathcal{S}}$ as

$$(E_\pi q)(s) = \sum_{a \in \mathcal{A}} \pi(s|a)q(s, a), \quad s \in \mathcal{S}.$$

(iii) $E_* : \mathbb{R}^{\mathcal{S} \times \mathcal{A}} \rightarrow \mathbb{R}^{\mathcal{S}}$ as

$$(E_*q)(s) = \max_{a \in \mathcal{A}} q(s, a), \quad s \in \mathcal{S}.$$

(iv) $B_\pi^{(V, \gamma)} = E_\pi \circ D^{(\gamma)}$ (Bellman expectation operator for state-value functions)

- (v) $B_*^{(V,\gamma)} = E_* \circ D^{(\gamma)}$ (Bellman optimality operator for state-value functions)
- (vi) $B_\pi^{(Q,\gamma)} = D^{(\gamma)} \circ E_\pi$ (Bellman expectation operator for action-value functions)
- (vii) $B_*^{(Q,\gamma)} = D^{(\gamma)} \circ E_*$ (Bellman optimality operator for action-value functions)

We will use lighter notation $D, E_\pi, E_*, B_\pi, B_*$ as soon as context prevents confusion. The following expressions follow from the definitions.

Proposition 2.1.2 (Explicit expression of Bellman operators). *Let $v \in \mathbb{R}^{\mathcal{S}}$, $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$, and π a stationary policy. Then, the following expressions hold.*

$$\begin{aligned}
(B_\pi v)(s) &= \sum_{(a,r,s') \in \mathcal{A} \times \mathcal{S} \times \mathcal{R}} \pi(a|s) p(r, s'|s, a) (r + \gamma v(s')), \quad s \in \mathcal{S}, \\
(B_* v)(s) &= \max_{a \in \mathcal{A}} \sum_{(r,s') \in \mathcal{S} \times \mathcal{R}} p(r, s'|s, a) (r + \gamma v(s')), \quad s \in \mathcal{S}, \\
(B_\pi q)(s, a) &= \sum_{(r,s',a') \in \mathcal{S} \times \mathcal{R} \times \mathcal{A}} p(r, s'|s, a) (r + \gamma \pi(a'|s') q(s', a')), \quad (s, a) \in \mathcal{S} \times \mathcal{A}, \\
(B_* q)(s, a) &= \sum_{(r,s') \in \mathcal{S} \times \mathcal{R}} p(r, s'|s, a) \left(r + \gamma \max_{a' \in \mathcal{A}} q(s', a') \right), \quad (s, a) \in \mathcal{S} \times \mathcal{A}.
\end{aligned}$$

Proof. Immediate from the definitions. \square

Proposition 2.1.3 (Bellman operators as expectations). *Let $v \in \mathbb{R}^{\mathcal{S}}$, $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$, π a policy, $s \in \mathcal{S}$, $a \in \mathcal{A}$. Then,*

$$(i) \quad (Dv)(s, a) = \mathbb{E}_{s,a,\pi} [R_1 + \gamma v(S_1)],$$

and if π is stationary,

$$(ii) \quad (E_\pi q)(s) = \mathbb{E}_{s,\pi} [q(s, A_0)],$$

$$(iii) \quad (B_\pi v)(s) = \mathbb{E}_{s,\pi} [R_1 + \gamma v(S_1)],$$

$$(iv) \quad (B_\pi q)(s, a) = \mathbb{E}_{s,a,\pi} [R_1 + \gamma q(S_1, A_1)].$$

$$(v) \quad (B_* v)(s) = \max_{a \in \mathcal{A}} \mathbb{E}_{s,a,\pi} [R_1 + \gamma v(S_1)],$$

$$(vi) \quad (B_* q)(s, a) = \mathbb{E}_{s,a,\pi} \left[R_1 + \gamma \max_{a' \in \mathcal{A}} q(S_1, a') \right].$$

Proof. Let us prove (i). Let π' the policy associated with (s, a) used in Definition 1.3.2 to define $\mathbb{P}_{s,a,\pi}$. Using the definition of the probability measure $\mathbb{P}_{s,\pi}$ (see Proposition 1.3.1),

$$\begin{aligned} \mathbb{E}_{s,a,\pi} [R_1 + \gamma v(S_1)] &= \mathbb{E}_{s,\pi'} [R_1 + \gamma v(S_1)] \\ &= \sum_{(r,s') \in \mathcal{R} \times \mathcal{S}} (r + \gamma v(s')) \\ &\quad \times \mathbb{P}_{s,\pi'} \left(\mathcal{S} \times \mathcal{A} \times \{r\} \times \{s'\} \times (\mathcal{R} \times \mathcal{S} \times \mathcal{A})^{\mathbb{N}} \right) \\ &= \sum_{(r,s') \in \mathcal{R} \times \mathcal{S}} p(r, s' | s, a) (r + \gamma v(s')) \\ &= (Dv)(s, a) \end{aligned}$$

We now turn to (ii).

$$\begin{aligned} E_{s,\pi} \mathbb{E} [q(s, A_0)] &= \sum_{a \in \mathcal{A}} q(s, a) \times \mathbb{P}_{s,a} \left(\mathcal{S} \times \{a\} \times (\mathcal{R} \times \mathcal{S} \times \mathcal{A})^{\mathbb{N}} \right) \\ &= \sum_{a \in \mathcal{A}} q(s, a) \pi(a | s) = (E_{\pi} q)(s). \end{aligned}$$

We now deduce (iii) using Proposition 1.3.3:

$$\begin{aligned} (B_{\pi} v)(s) &= (E_{\pi} (Dv))(s) = \sum_{a \in \mathcal{A}} \pi(a | s) \mathbb{E}_{s,a,\pi} [R_1 + \gamma v(S_1)] \\ &= \mathbb{E}_{s,\pi} [R_1 + \gamma v(S_1)]. \end{aligned}$$

For (iv), we combine (i) and (ii) with the help of the Markov property from Proposition 1.3.4; let $(S'_0, A'_0, R'_1, \dots) \sim \mathbb{P}_{s,a,\pi}$, then

$$\begin{aligned} (B_{\pi} q)(s, a) &= (D(E_{\pi} q))(s, a) = \mathbb{E} [R'_1 + \gamma (E_{\pi} q)(S'_1)] \\ &= \mathbb{E} \left[R'_1 + \gamma \cdot \mathbb{E}_{S'_1, \pi} [q(S'_0, A'_0)] \right] \\ &= \mathbb{E} \left[R'_1 + \gamma \cdot \mathbb{E} [q(S'_1, A'_1) | S'_1] \right] \\ &= \mathbb{E} [R'_1 + \gamma \cdot q(S'_1, A'_1)]. \end{aligned}$$

Finally, (v) and (vi) follow by composition. \square

Remark 2.1.4. If for each $s \in \mathcal{S}$, $v(s)$ is interpreted as an estimate of the total reward obtained starting from state s and using policy π , $(B_{\pi} v)(s)$ is then an alternative estimate, as it is the expectation, when starting from state s of the actual first reward R_1 , plus $\lambda v(S_1)$ which is an estimate of remaining discounted rewards, as estimated by v . A similar interpretation holds for $B_{\pi} q$. We will see that the latter estimate is in some sense better: the Bellman operators will thus be used to iteratively *update* the estimates.

Definition 2.1.5. Let $d, n \geq 1$ integers. A map $F : \mathbb{R}^d \rightarrow \mathbb{R}^n$ is *monotone* if for all $x, x' \in \mathbb{R}^d$, $x \leq x'$ implies $Fx \leq Fx'$, where the inequalities are to be understood component-wise.

Proposition 2.1.6. Let π be a stationary policy. Then, operators D , E_π , $B_\pi^{(V)}$ and $B_\pi^{(Q)}$ are affine with nonnegative coefficients. E_π is moreover linear. In particular, they are monotone.

Proof. Immediate from the definitions. \square

Proposition 2.1.7. Let $v \in \mathbb{R}^{\mathcal{S}}$, $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$, $s \in \mathcal{S}$ and $a \in \mathcal{A}$. Then,

$$(i) \quad (E_* q)(s) = \sup_{\pi \in \Pi_0} (E_\pi q)(s) = \sup_{\pi \in \Pi_{0,d}} (E_\pi q)(s),$$

$$(ii) \quad (B_* v)(s) = \sup_{\pi \in \Pi_0} (B_\pi v)(s) = \sup_{\pi \in \Pi_{0,d}} (B_\pi v)(s),$$

$$(iii) \quad (B_* q)(s, a) = \sup_{\pi \in \Pi_0} (B_\pi q)(s, a) = \sup_{\pi \in \Pi_{0,d}} (B_\pi q)(s, a).$$

Proof. (i) is an easy consequence from the definition of E_* . Then (ii) and (iii) follow using the monotonicity from Proposition 2.1.6. \square

2.2 Bellman equations

Definition 2.2.1. Let X be a set and $F : X \rightarrow X$. An element $x \in X$ is a *fixed point* of F is $Fx = x$.

The fixed points of Bellman operators will be of particular interest. They are often written in the form of the so-called Bellman equations: for a given stationary policy π , a state-value function $v \in \mathbb{R}^{\mathcal{S}}$ is a fixed point of $B_\pi^{(V)}$ if, and only if:

$$v(s) = \sum_{(a,r,s') \in \mathcal{A} \times \mathcal{S} \times \mathcal{R}} \pi(a|s) p(r, s'|s, a) (r + \gamma v(s')), \quad s \in \mathcal{S}.$$

The above is called the *Bellman expectation equation* for state-value functions. Similarly, v is the fixed point of $B_*^{(V)}$ if, and only if:

$$v(s) = \max_{a \in \mathcal{A}} \sum_{(r,s') \in \mathcal{S} \times \mathcal{R}} p(r, s'|s, a) (r + \gamma v(s')), \quad s \in \mathcal{S},$$

which is called the Bellman *optimality equation*. The corresponding equations for action-value functions are similarly defined. We establish below that these equations have unique solutions and that they correspond respectively to v_π and v_* , where v_* is the value function associated with an optimal policy.

Theorem 2.2.2 (Banach's fixed point theorem). *Let $0 \leq \gamma < 1$, (X, d) a complete metric space, and $F : X \rightarrow X$ a γ -Lipschitz map (with respect to distance d). Then, F has a unique fixed point $x_* \in X$ and for all sequence $(x_k)_{k \geq 0}$ satisfying $x_{k+1} = Fx_k$ ($k \geq 0$), it holds that*

$$d(x_k, x_*) \leq \gamma^k d(x_0, x_*), \quad k \geq 0,$$

and thus $x_k \rightarrow x_*$ as $k \rightarrow +\infty$.

Remark 2.2.3. The above convergence is guaranteed regardless of the initial point x_0 .

Proposition 2.2.4. *Let π be a stationary policy. With respect to the norms $\|\cdot\|_\infty$ in $\mathbb{R}^{\mathcal{S}}$ and $\mathbb{R}^{\mathcal{S} \times \mathcal{A}}$,*

(i) $D^{(\gamma)}$ is γ -Lipschitz continuous,

(ii) E_π is 1-Lipschitz continuous,

(iii) E_* is 1-Lipschitz continuous,

(iv) $B_\pi^{(V, \gamma)}$, $B_*^{(V, \gamma)}$, $B_\pi^{(Q, \gamma)}$ and $B_*^{(Q, \gamma)}$ are γ -Lipschitz continuous and admit unique fixed points.

Proof. Let $v, v' \in \mathbb{R}^{\mathcal{S}}$.

$$\begin{aligned} \|Dv' - Dv\|_\infty &= \max_{(s, a) \in \mathcal{S} \times \mathcal{A}} |Dv'(s, a) - Dv(s, a)| \\ &= \max_{(s, a) \in \mathcal{S} \times \mathcal{A}} \left| \sum_{(r, s') \in \mathcal{R} \times \mathcal{S}} p(r, s' | s, a) \gamma (v'(s') - v(s)) \right| \\ &\leq \max_{(s, a) \in \mathcal{S} \times \mathcal{A}} \gamma \|v' - v\|_\infty \sum_{(r, s') \in \mathcal{R} \times \mathcal{S}} p(r, s' | s, a) \\ &= \gamma \|v' - v\|_\infty, \end{aligned}$$

where the last inequality follows from $p(\cdot | s, a)$ being a probability distribution over $\mathcal{R} \times \mathcal{S}$, which proves (i).

Let $q, q' \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ and π a stationary policy.

$$\begin{aligned} \|E_\pi q' - E_\pi q\|_\infty &= \max_{s \in \mathcal{S}} \left| \sum_{a \in \mathcal{A}} \pi(a | s) |q'(s, a) - q(s, a)| \right| \\ &\leq \max_{s \in \mathcal{S}} \sum_{a \in \mathcal{A}} \pi(a | s) \|q' - q\|_\infty \\ &= \|q' - q\|_\infty, \end{aligned}$$

where the last inequality follows from $\pi(\cdot | s)$ being a probability distribution over \mathcal{A} .

Let $s \in \mathcal{S}$. If $(E_*q')(s) \geq (E_*q)(s)$, then

$$\begin{aligned} |(E_*q')(s) - (E_*q)(s)| &= (E_*q')(s) - (E_*q)(s) \\ &= \max_{a' \in \mathcal{A}} q'(s, a') - \max_{a \in \mathcal{A}} q(s, a) \\ &\leq \max_{a' \in \mathcal{A}} \{q'(s, a') - q(s, a')\} \\ &\leq \max_{a' \in \mathcal{A}} |q'(s, a') - q(s, a')| \\ &\leq \|q' - q\|_\infty. \end{aligned}$$

Similarly, if $(E_*q')(s) \leq (E_*q)(s)$, then

$$|E_*q'(s) - E_*q(s)| \leq \|q' - q\|_\infty.$$

Taking the maximum over $s \in \mathcal{S}$ yields (iii):

$$\|E_*q' - E_*q\|_\infty \leq \|q' - q\|_\infty.$$

The Lipschitz property (iv) of Bellman operators then follow by composition. \square

Proposition 2.2.5. *Let π be a stationary policy. Then,*

$$(i) \quad v_\pi = E_\pi q_\pi,$$

$$(ii) \quad q_\pi = Dv_\pi,$$

$$(iii) \quad v_\pi \text{ is the unique fixed point of } B_\pi^{(V)},$$

$$(iv) \quad q_\pi \text{ is the unique fixed point of } B_\pi^{(Q)}.$$

Proof. Let $s \in \mathcal{S}$. We prove (i) using Proposition 1.3.3:

$$\begin{aligned} (E_\pi q_\pi)(s) &= \sum_{a \in \mathcal{A}} \pi(a|s) \cdot \mathbb{E}_{s,a,\pi} \left[\sum_{t=1}^{+\infty} \gamma^{t-1} R_t \right] \\ &= \mathbb{E}_{s,\pi} \left[\sum_{t=1}^{+\infty} \gamma^{t-1} R_t \right] \\ &= v_\pi. \end{aligned}$$

We now turn to (ii). Let $a \in \mathcal{A}$. Let $(S'_0, A'_0, R'_1, \dots) \sim \mathbb{P}_{s,a,\pi}$. Then, using the expression of the Bellman operator as an expectation (from Propo-

sition 2.1.3), we write

$$\begin{aligned}
(Dv_\pi)(s, a) &= \mathbb{E}_{s,a,\pi} [R_1 + \gamma v_\pi(S_1)] \\
&= \mathbb{E} [R'_1 + \gamma v_\pi(S'_1)] \\
&= \mathbb{E} \left[R'_1 + \gamma \cdot \mathbb{E}_{S'_1, \pi} \left[\sum_{t=1}^{+\infty} \gamma^{t-1} R_t \right] \right] \\
&= \mathbb{E} \left[R'_1 + \gamma \cdot \mathbb{E} \left[\sum_{t=1}^{+\infty} \gamma^{t-1} R'_{t+1} \middle| S'_1 \right] \right] \\
&= \mathbb{E} \left[\sum_{t=1}^{+\infty} \gamma^{t-1} R_t \right] = v_\pi,
\end{aligned}$$

where for the fourth equality we used the Markov property for $\mathbb{P}_{s,a,\pi}$ from Proposition 1.3.4.

Combining (i) and (ii) together with Banach's fixed point theorem from Theorem (2.2.2) yields (iv) and (v). \square

Remark 2.2.6. In other words, v_π (resp. q_π) is the unique solution of the Bellman expectation equation for state-value function (resp. action-value functions).

2.3 Greedy policies

Definition 2.3.1. A stationary and deterministic policy $\pi : \mathcal{S} \rightarrow \mathcal{A}$ is

- (i) a *greedy policy* with respect to an action-value function $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ if for all $s \in \mathcal{S}$,

$$\pi(s) \in \operatorname{Arg max}_{a \in \mathcal{A}} q(s, a),$$

where $\operatorname{Arg max}$ denotes the set of maximizers.

- (ii) a *greedy policy* with respect to an state-value function $v \in \mathbb{R}^{\mathcal{S}}$ if $\pi \in \Pi_g [Dv]$.

$\Pi_g [q]$ denotes the set of greedy policies with respect to q and $\Pi_g [v]$ is a shorthand for $\Pi_g [Dv]$. Notation $\pi_g [q]$ (resp. $\pi_g [v]$) denotes any element from $\Pi_g [q]$ (resp. $\Pi_g [v]$).

Remark 2.3.2. $\pi_g [q]$ corresponds to a policy which selects actions by simply comparing values of the action-value function q . In the case of $\pi_g [v]$, the action selection is based on a *one-step look-ahead*, as it rewrites as follows using Proposition 2.1.3:

$$\pi_g(s) \in \operatorname{Arg max}_{a \in \mathcal{A}} \mathbb{E}_{s,a,\pi} [R_1 + \gamma v(S_1)].$$

Proposition 2.3.3. For $v \in \mathbb{R}^{\mathcal{S}}$ (resp. $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$), $\Pi_g[v]$ (resp. $\Pi_g[q]$) is nonempty.

Proof. The set of actions \mathcal{A} being finite (and nonempty), $\text{Arg max}_{a \in \mathcal{A}} q(s, a)$ is nonempty, and the result follows. \square

Proposition 2.3.4. Let $v \in \mathbb{R}^{\mathcal{S}}$ and $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$. Then,

$$(i) \ E_*q = E_{\pi_g[q]}q,$$

$$(ii) \ B_*q = B_{\pi_g[q]}q.$$

$$(iii) \ B_*v = B_{\pi_g[v]}v,$$

Proof. Let $s \in \mathcal{S}$ and $\pi \in \Pi_g[q]$. By definition of a greedy policy,

$$(E_*q)(s) = \max_{a \in \mathcal{A}} q(s, a) = q(s, \pi(s)) = \sum_{a \in \mathcal{A}} \pi(s|a)q(s, a) = (E_\pi q)(s).$$

Then, $B_*^{(Q)}q = D \circ E_* = D \circ E_\pi = B_\pi$ and $B_*^{(V)}q = E_* \circ D = E_\pi \circ D = B_\pi$. \square

2.4 Optimal value functions & policies

Definition 2.4.1. Let $\gamma \in (0, 1)$. The *optimal state-value* and *actions-value functions* with respect to discount factor γ are respectively defined as

$$\begin{aligned} v_*^{(\gamma)}(s) &= \sup_{\pi \in \Pi} v_\pi^{(\gamma)}(s), \quad s \in \mathcal{S}, \\ q_*^{(\gamma)}(s, a) &= \sup_{\pi \in \Pi} q_\pi^{(\gamma)}(s, a), \quad (s, a) \in \mathcal{S} \times \mathcal{A}. \end{aligned}$$

As soon as discount factor γ is clear from the context, we may simply use notation v_* and q_* .

Remark 2.4.2. v_* and q_* are well-defined because v_π and q_π can be easily seen to be bounded by $(1 - \gamma)^{-1} \max_{r \in \mathbb{R}} |r|$.

Definition 2.4.3. A policy π_* is *optimal* if $v_{\pi_*} = v_*$.

Theorem 2.4.4. Let v_0 and q_0 the unique fixed points of $B_*^{(V)}$ and $B_*^{(Q)}$ respectively. Then, $\Pi_g[v_0] = \Pi_g[q_0]$ and for π_g in the latter set,

$$(i) \ v_* = v_0 = v_{\pi_g},$$

$$(ii) \ q_* = q_0 = q_{\pi_g},$$

$$(iii) \ v_* = E_*q_*,$$

$$(iv) \ q_* = Dv_*.$$

Remark 2.4.5. Some important takeaways from the above theorem are the following:

- v_* (resp. q_*) is the unique fixed point of $B_*^{(V)}$ (resp. $B_*^{(Q)}$), meaning the unique solution to the Bellman optimality equation for state-value function (resp. action-value function);
- there exists a stationary and deterministic optimal policy.

Proof. Let us first prove that $q_0 = Dv_0$ and $v_0 = E_*q_0$. Indeed,

$$Dv_0 = DB_*v_0 = DE_*Dv_0 = B_*(Dv_0),$$

therefore, Dv_0 is the unique fixed point of B_* , in other words $q_0 = Dv_0$. Then,

$$E_*q_0 = E_*Dv_0 = B_*v_0 = v_0.$$

Therefore, $\Pi_g[v_0] = \Pi_g[Dv_0] = \Pi_g[q_0]$. We recall that a set of greedy policies is never empty, as stated in Proposition 2.3.3.

Let $\pi_g \in \Pi_g[v_0]$. Then using the property of greedy policies from Proposition 2.3.4, $v_0 = B_*v_0 = B_{\pi_g}v_0$ and $q_0 = B_*q_0 = B_{\pi_g}q_0$. Value functions v_0 and q_0 are therefore the unique fixed points of $B_{\pi_g}^{(V)}$ and $B_{\pi_g}^{(Q)}$, respectively. In other words $v_0 = v_{\pi_g}$ and $q_0 = q_{\pi_g}$, by Proposition 2.2.5.

Therefore, $v_0 = v_{\pi_g} \leq \sup_{\pi \in \Pi_{0,d}} v_\pi$ because $\pi_g \in \Pi_{0,d}$ by definition, and similarly $q_0 \leq \sup_{\pi \in \Pi_{0,d}} q_\pi$.

Let us now prove that $v_0 \geq \sup_{\pi \in \Pi} v_\pi$. Let $\pi = (\pi_t)_{t \geq 0}$ be any policy, $s \in \mathcal{S}$, and consider random variables $(S_0, A_0, R_1, S_2, A_2, R_3, \dots) \sim \mathbb{P}_{s,\pi}$. Let $t \geq 0$,

$$v_0(S_t) = (B_*v_0)(S_t) = \max_{a \in \mathcal{A}} (Dv)(S_t, a) \geq (Dv)(S_t, A_t).$$

Let us rewrite this last quantity. Let $(s_0, a_0) \in \mathcal{S}$ such that $\mathbb{P}[S_t = s_0, A_t = a_0] > 0$. Then, using the definition of $\mathbb{P}_{s,\pi}$,

$$\begin{aligned} (Dv)(s_0, a_0) &= \sum_{(r,s') \in \mathcal{R} \times \mathcal{S}} p(r, s' | s_0, a_0) (r + \gamma v(s')) \\ &= \sum_{(r,s') \in \mathcal{R} \times \mathcal{S}} \frac{\mathbb{P}[R_{t+1} = r, S_{t+1} = s', S_t = s_0, A_t = a_0]}{\mathbb{P}[S_t = s_0, A_t = a_0]} (r + \gamma v(s')) \\ &= \mathbb{E}[R_{t+1} + \gamma v(S_{t+1}) | S_t, A_t]. \end{aligned}$$

Therefore,

$$v_0(S_t) \geq \mathbb{E}[R_{t+1} + \gamma v(S_{t+1}) | S_t, A_t].$$

Then using the expression of $(Bv_0)(s)$ from Proposition 2.1.3, applying the above recursively, we get

$$\begin{aligned}
 v_0(s) &= (Bv_0)(s) = \mathbb{E}[R_1 + \gamma v_0(S_1)] \\
 &\geq \mathbb{E}[R_1 + \gamma \mathbb{E}[R_2 + \gamma v(S_2) | S_1, A_1]] \\
 &\geq \dots \geq \mathbb{E}_{s,\pi} \left[\sum_{t=1}^T \gamma^{t-1} R_t + \gamma^T v(S_T) \right] \\
 &\geq \mathbb{E} \left[\sum_{t=1}^{+\infty} \gamma^{t-1} R_t \right] = v_\pi(s).
 \end{aligned}$$

Therefore,

$$v_* = \sup_{\pi \in \Pi} v_\pi \leq v_0 = v_{\pi_g} \leq \sup_{\pi \in \Pi_{0,d}} v_\pi \leq \sup_{\pi \in \Pi} v_\pi = v_*,$$

and the lower and upper bounds being equal, all inequalities are equalities, and the supremums are maximums because they are attained for $\pi_g \in \Pi_{0,d} \subset \Pi$.

Then, we write

$$\begin{aligned}
 q_* &= \sup_{\pi \in \Pi} q_\pi \geq \max_{\pi \in \Pi_{0,d}} q_\pi \geq q_{\pi_g} = q_0 = Dv_0 \\
 &= D \left(\max_{\pi \in \Pi} v_\pi \right) \geq \sup_{\pi \in \Pi} Dv_\pi = \sup_{\pi \in \Pi} q_\pi = q_*,
 \end{aligned}$$

where the last inequality holds by monotonicity of D from Proposition 2.1.6 (by writing for $\pi \in \Pi$, $D \max_{\pi \in \Pi} v_\pi \geq Dv_\pi$ and then taking the supremum over $\pi \in \Pi$). Therefore, all inequalities are equalities and all supremums are maximums. \square

Chapter 3

Dynamic programming

The properties of the Bellman operators established in the previous chapter allow the construction and analysis of dynamic programming algorithms (DP), meaning algorithms that solve MDPs with known dynamics. Starting from Chapter 4, we will study reinforcement learning, which is solving MDPs with either unknown dynamics, and/or by approximating the problem in some way. Most reinforcement learning methods (RL) are sample variants of dynamic programming algorithms.

3.1 Value iteration

Policy evaluation is the computation of the value function v_π or q_π of a policy π . Many dynamic programming and reinforcement learning algorithms use policy evaluation as an intermediate step in finding the optimal policy. The (synchronous) value iteration for policy evaluation computes v_π (or q_π), in the case of a stationary policy, by iterating the Bellman expectation operator $B_\pi^{(V)}$ (resp. $B_\pi^{(Q)}$). *Synchronous* means that all values (for each state, or each state-action pair) are updated simultaneously using the values from the current iterate.

In the context of MDPs, *control* is the computation of an optimal optimal policy. The (synchronous) value iteration for control approximately computes v_* (resp. q_*) by iterating the Bellman expectation operator $B_*^{(V)}$ (resp. $B_*^{(Q)}$) and then considers a greedy policy.

Definition 3.1.1 (Synchronous value iteration). Let π be a stationary policy, $(v_k)_{k \geq 0}$ and $(q_k)_{k \geq 0}$ two sequences in \mathbb{R}^S and $\mathbb{R}^{S \times \mathcal{A}}$ respectively.

- (i) $(v_k)_{k \geq 0}$ (resp. $(q_k)_{k \geq 0}$) is a *synchronous state-value* (resp. *action-value*) iteration for the evaluation of π if for all $k \geq 0$,

$$v_{k+1} = B_\pi v_k, \quad (\text{resp. } q_{k+1} = B_\pi q_k)$$

- (ii) $(v_k)_{k \geq 0}$ (resp. $(q_k)_{k \geq 0}$) is a *synchronous state-value* (resp. *action-value*) iteration for control if for all $k \geq 0$,

$$v_{k+1} = B_* v_k, \quad (\text{resp. } q_{k+1} = B_* q_k).$$

Remark 3.1.2. Value iterations for state-value functions explicitly write as

$$v_{k+1}(s) = \sum_{(a,r,s') \in \mathcal{A} \times \mathcal{S} \times \mathcal{R}} \pi(a|s) p(r, s'|s, a) (r + \gamma v_k(s')), \quad s \in \mathcal{S}, \quad k \geq 0,$$

for the evaluation of π , and as

$$v_{k+1}(s) = \max_{a \in \mathcal{A}} \sum_{(r,s') \in \mathcal{S} \times \mathcal{R}} p(r, s'|s, a) (r + \gamma v_k(s')), \quad s \in \mathcal{S}, \quad k \geq 0,$$

for control. Similar expression hold for action-value functions.

Proposition 3.1.3 (Equivalence between synchronous state-value and action-value iterations). *Let π be a stationary policy, $(v_k)_{k \geq 0}$ and $(q_k)_{k \geq 0}$ two sequences in $\mathbb{R}^{\mathcal{S}}$ and $\mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ respectively. Consider the following assertions.*

- | | |
|--|--|
| (a) $\forall k \geq 0, \quad v_{k+1} = B_\pi v_k;$ | (e) $\forall k \geq 0, \quad q_k = Dv_k;$ |
| (b) $\forall k \geq 0, \quad q_{k+1} = B_\pi q_k;$ | (f) $\forall k \geq 0, \quad v_k = E_\pi q_k;$ |
| (c) $\forall k \geq 0, \quad v_{k+1} = B_* v_k;$ | (g) $\forall k \geq 0, \quad v_k = E_* q_k.$ |
| (d) $\forall k \geq 0, \quad q_{k+1} = B_* q_k;$ | |

Then,

- | | |
|-----------------------------|------------------------------|
| (i) (a) and (e) imply (b), | (iii) (c) and (e) imply (d), |
| (ii) (b) and (f) imply (a), | (iv) (d) and (g) imply (c). |

Proof. Assume (a) and (e). Then for all $k \geq 0$,

$$B_\pi q_k = DE_\pi Dv_k = DB_\pi v_k = Dv_{k+1} = q_{k+1},$$

and (b) holds. The other implications are proved similarly. \square

Proposition 3.1.4 (Linear convergence of synchronous value iteration). *Let π be a stationary policy.*

- If $(v_k)_{k \geq 0}$ and $(q_k)_{k \geq 0}$ are synchronous state-value (resp. action-value) iterations for the evaluation of policy π , then for all $k \geq 0$,

$$\begin{aligned} \|v_k - v_\pi\|_\infty &\leq \gamma^k \|v_0 - v_\pi\|_\infty, \\ \|q_k - q_\pi\|_\infty &\leq \gamma^k \|q_0 - q_\pi\|_\infty. \end{aligned}$$

- If $(v_k)_{k \geq 0}$ and $(q_k)_{k \geq 0}$ are synchronous state-value (resp. action-value) iterations for control, then for all $k \geq 0$,

$$\begin{aligned} \|v_k - v_*\|_\infty &\leq \gamma^k \|v_0 - v_*\|_\infty, \\ \|q_k - q_*\|_\infty &\leq \gamma^k \|q_0 - q_*\|_\infty. \end{aligned}$$

Proof. We know from Proposition 2.2.5 and Theorem 2.4.4 that v_π (resp. q_π , v_* , q_*) is the unique fixed point of Bellman operator $B_\pi^{(V)}$ (resp. $B_\pi^{(Q)}$, $B_*^{(V)}$, $B_*^{(Q)}$). The latter is γ -Lipschitz continuous with respect to $\|\cdot\|_\infty$ according to Proposition 2.2.4. The Banach's fixed point theorem (Theorem 2.2.2) then applies and gives the result. \square

Remark 3.1.5 (Computational complexity and memory requirements). The above results demonstrate that both algorithms for policy evaluation (resp. control) are equivalent in terms of output solutions. However, memory requirements of the state-value counterpart are lower by a factor $|\mathcal{A}|$. There is therefore no reason to choose action-value iteration in the context of dynamic programming. In reinforcement learning however, the additional stored values of the latter will be of great help.

3.2 Policy iteration

Proposition 3.2.1 (Greedy policy improvement). *Let π be a stationary policy and $\pi_g \in \Pi_g[v_\pi]$. Then,*

- (i) $v_{\pi_g} \geq v_\pi$,
- (ii) $q_{\pi_g} \geq q_\pi$,
- (iii) $v_{\pi_g} = v_\pi$ implies $v_\pi = v_*$,
- (iv) $q_{\pi_g} = q_\pi$ implies $q_\pi = q_*$.

Proof. Using the fact that v_π is a fixed point of B_π (Proposition 2.2.5), the property $B_* = \sup_{\pi_0 \in \Pi_0} B_{\pi_0}$ from Proposition 2.1.7 and the property of greedy policies from Proposition 2.3.4,

$$v_\pi = B_\pi v_\pi \leq B_* v_\pi = B_{\pi_g} v_\pi.$$

Then, applying on both sides operator B_{π_g} , which is monotone thanks to Proposition 2.1.6, we get $B_{\pi_g} v_\pi \leq B_{\pi_g}^2 v_\pi$. Therefore, $v_\pi \leq B_{\pi_g}^k v_\pi$ for all $k \geq 1$, and by Proposition 3.1.4, taking the limit as $k \rightarrow +\infty$ gives (i). Besides, using the monotonicity of D from Proposition 2.1.6, together with Proposition 2.2.5 gives (ii):

$$q_\pi = Dv_\pi \leq Dv_{\pi_g} \leq q_{\pi_g}.$$

Using Propositions 2.2.5 and 2.3.4, we write $v_\pi = v_{\pi_g} = B_{\pi_g} v_{\pi_g} = B_{\pi_g} v_\pi = B_* v_\pi$. Thus, v_π is a fixed point of B_* , and $v_\pi = v_*$ by Theorem 2.4.4, which proves (iii). (iv) is proved similarly. \square

Definition 3.2.2 (Policy iteration). A sequence $(\pi_k)_{k \geq 0}$ of stationary policies is a *policy iteration* if $\pi_{k+1} \in \Pi_g[v_{\pi_k}]$ for all $k \geq 0$.

Remark 3.2.3 (Policy iteration is an idealized algorithm). Except in situations where v_{π_k} can be computed exactly, policy iteration is only an idealized algorithm because each step would involve the computation of v_{π_k} by iterating B_{π_k} infinitely. A practical variant, where B_{π_k} is only iterated a finite number of times is discussed in Remark 3.2.6 below.

Remark 3.2.4 (Equivalent definition from action-value functions). Policy iteration can be written with action-value functions:

$$\pi_{k+1} \in \Pi_g[q_{\pi_k}],$$

which is equivalent to the above, because by definition of greedy policies for state-value functions gives:

$$\Pi_g[v_{\pi_k}] = \Pi_g[Dv_{\pi_k}] = \Pi_g[q_{\pi_k}],$$

where we used Proposition 2.2.5 for the last equality. Unlike value iterations, the corresponding algorithm is exactly the same even regarding the computational and memory requirements, because determining a greedy policy in $\Pi_g[v_{\pi_k}]$ requires by definition the computation of $Dv_{\pi_k} = q_{\pi_k}$.

Proposition 3.2.5 (Linear convergence of policy iteration). *Let $(\pi_k)_{k \geq 0}$ be a policy iteration. Then for all $k \geq 0$,*

$$\begin{aligned} \|v_{\pi_k} - v_*\|_\infty &\leq \gamma^k \|v_{\pi_0} - v_*\|_\infty, \\ \|q_{\pi_k} - q_*\|_\infty &\leq \gamma^k \|q_{\pi_0} - q_*\|_\infty. \end{aligned}$$

Proof. Denote $v_k = v_{\pi_k}$ for $k \geq 0$.

$$\begin{aligned} v_* - v_{k+1} &= B_*v_* - B_*v_k + (B_* - B_{\pi_{k+1}})v_k + B_{\pi_{k+1}}(v_k - v_{k+1}) \\ &\leq B_*v_* - B_*v_k, \end{aligned}$$

where the inequality holds because the second term is zero:

$$B_{\pi_{k+1}}v_k = B_{\pi_g[v_k]}v_k = B_*v_k$$

and the last term is nonpositive because $B_{\pi_{k+1}}$ is monotone according to Proposition 2.1.6, and $v_k \leq v_{k+1}$ by property of greedy policy improvement from Proposition 3.2.1. Moreover, by definition of v_* , $v_* \geq v_{\pi_{k+1}} = v_{k+1}$. Therefore,

$$0 \leq v_* - v_{k+1} \leq B_*v_* - B_*v_k$$

and using the Lipschitz continuity of B_* from Proposition 2.2.4,

$$\|v_* - v_{k+1}\|_\infty \leq \|B_*v_* - B_*v_k\|_\infty \leq \gamma \|v_* - v_k\|_\infty.$$

The result for action-value functions is proved similarly. \square

Remark 3.2.6 (Generalized iteration). It is possible to define a family of iterations, which generalizes both value iteration and policy iteration. It is sometimes called *generalized policy iteration* or *optimistic policy iteration*. A sequence $(v_k)_{k \geq 0}$ in \mathbb{R}^S (resp. $(q_k)_{k \geq 0}$ in $\mathbb{R}^{S \times \mathcal{A}}$) is a *generalized iteration* for state-value functions (resp. action-value functions) if there exists a sequence $(m_k)_{k \geq 0}$ in $\{1, 2, \dots\} \cup \{\infty\}$ such that for all $k \geq 0$,

$$\begin{aligned} \pi_k &\in \Pi_g[v_k], & (\text{resp. } \pi_k &\in \Pi_g[q_k]) \\ v_{k+1} &= B_{\pi_k}^{m_k} v_k, & (\text{resp. } q_{k+1} &= B_{\pi_k}^{m_k} q_k), \end{aligned}$$

where by convention, $B_{\pi}^{\infty} v = v_{\pi}$ (for all $\pi \in \Pi_0$ and $v \in \mathbb{R}^{S \times \mathcal{A}}$). Then, value iteration corresponds to $m_k = 1$ (for all $k \geq 0$) and policy iteration corresponds to $m_k = \infty$ (for all $k \geq 0$). A practical implementation of policy iteration where m_k may be large but not infinite then belongs to this family.

3.3 Asynchronous fixed point iterations

Theorem 3.3.1 (A generalized fixed point theorem). *Let (X, d) a metric space, $(\gamma_k)_{k \geq 0}$ nonnegative sequence in $(0, 1)$ and $(F_k)_{k \geq 0}$ a sequence of operators in X that share a common fixed point $x_* \in X$ and so that F_k is γ_k -Lipschitz continuous. If $(x_k)_{k \geq 0}$ satisfies $x_{k+1} = F_k x_k$ for all $k \geq 0$, then*

$$d(x_k, x_*) \leq d(x_0, x_*) \left(\prod_{\ell=0}^{k-1} \gamma_{\ell} \right).$$

If the above product converges to zero, then $x_k \rightarrow x_$ as $k \rightarrow +\infty$.*

Proof. Let $k \geq 0$.

$$d(x_{k+1}, x_*) = d(F_k x_k, F_k x_*) \leq \gamma_k d(x_k, x_*),$$

hence the result. \square

For the remaining of this section, $d \geq 1$ will be a given integer.

Definition 3.3.2. Let $F : \mathbb{R}^d \rightarrow \mathbb{R}^d$. For $J \subset \{1, \dots, d\}$ and denote $F^{|J|} : \mathbb{R}^d \rightarrow \mathbb{R}^d$ the operator defined as

$$(F^{|J|} x)_j = (F x)_j$$

for $j \in J$ and $(F^{|J|} x)_{j'} = x_{j'}$ for $j' \notin J$. If $J = \{j\}$ for some $j \in \{1, \dots, d\}$, we denote $F^{|j|} = F^{\{j\}}$.

Remark 3.3.3. $F^{|J|}$ can be written as

$$F^{|J|} = I + \mathbb{1}_J \otimes (F - I) = (1 - \mathbb{1}_J) \otimes I + \mathbb{1}_J \otimes F$$

where $\mathbb{1}_J$ denotes the vector with value 1 for components in J and value 0 for the other components, and \otimes denotes component-wise multiplication. This expression will be easier to generalize.

Proposition 3.3.4. *Let $F : \mathbb{R}^d \rightarrow \mathbb{R}^d$ be a 1-Lipschitz continuous map for $\|\cdot\|_\infty$. Then for all $J \subset \{1, \dots, d\}$, $F^{|J|}$ is 1-Lipschitz continuous for $\|\cdot\|_\infty$.*

Proof. For $x, x' \in \mathbb{R}^d$,

$$\begin{aligned} \|F^{|J|}x - F^{|J|}x'\|_\infty &= \max_{1 \leq j \leq d} |(F^{|J|}x)_j - (F^{|J|}x')_j| \\ &= \max \left\{ \max_{j \in J} |(F^{|J|}x)_j - (F^{|J|}x')_j|, \max_{j \notin J} |(F^{|J|}x)_j - (F^{|J|}x')_j| \right\} \\ &\leq \max \left\{ \max_{j \in J} |(Fx)_j - (Fx')_j|, \max_{j \notin J} |x_j - x'_j| \right\} \\ &\leq \max \{ \|Fx - Fx'\|_\infty, \|x - x'\|_\infty \} \\ &\leq \|x - x'\|_\infty. \end{aligned}$$

□

Proposition 3.3.5. *Let $F : \mathbb{R}^d \rightarrow \mathbb{R}^d$ and $x \in \mathbb{R}^d$. The following propositions are equivalent:*

- (i) x a fixed point of F ,
- (ii) x a is fixed point of $F^{|j|}$ for all $j \in \{1, \dots, d\}$,
- (iii) x a is fixed point of $F^{|J|}$ for all $J \subset \{1, \dots, d\}$.

Proof. Immediate

□

Proposition 3.3.6. *Let $\gamma \in [0, 1]$ and $F : \mathbb{R}^d \rightarrow \mathbb{R}^d$ a γ -Lipschitz continuous map for $\|\cdot\|_\infty$. Let J_1, \dots, J_M be such that $\bigcup_{m=1}^M J_m = \{1, \dots, d\}$. Then, $F^{|J_M|} \circ \dots \circ F^{|J_1|}$ is γ -Lipschitz continuous for $\|\cdot\|_\infty$.*

Proof. For each $1 \leq m \leq M$, denote $F^{1:m} = F^{|J_m|} \circ F^{|J_{m-1}|} \circ \dots \circ F^{|J_1|}$.

Now fix $1 \leq j \leq d$ and let m be an integer such that $j \in J_m$. Then it follows that,

$$(F^{1:M}x)_j = (F^{|J_M|}(F^{1:M-1}x))_j = (F^{1:M-1}x)_j = \dots = (F^{1:m}x)_j = (F(F^{1:m-1}x))_j.$$

Similarly, $(F^{1:M}x')_j = (F(F^{1:m-1}x'))_j$. Then using the above,

$$\begin{aligned} |(F^{1:M}x)_j - (F^{1:M}x')_j| &= |(F(F^{1:m-1}x))_j - (F(F^{1:m-1}x'))_j| \\ &\leq \|F(F^{1:m-1}x) - F(F^{1:m-1}x')\|_\infty \\ &\leq \gamma \|F^{1:m-1}x - F^{1:m-1}x'\|_\infty \\ &\leq \gamma \|x - x'\|_\infty, \end{aligned}$$

where we used the γ -Lipschitz property of F and for the last inequality the 1-Lipschitz continuity of each map F_1, F_2, \dots, F_{m-1} from Proposition 3.3.4. Taking the maximum over j yields

$$\|F^{1:M}x - F^{1:M}x'\|_\infty \leq \gamma \|x - x'\|_\infty.$$

□

Theorem 3.3.7. *Let $\gamma \in (0, 1)$, $F : \mathbb{R}^d \rightarrow \mathbb{R}^d$ a γ -Lipschitz continuous map for $\|\cdot\|_\infty$, and $(J_k)_{k \geq 0}$ a sequence of sets so that each $j \in \{1, \dots, d\}$ belongs to infinitely many sets. If $(x_k)_{k \geq 0}$ satisfies*

$$x_{k+1} = F^{|J_k|} x_k,$$

then it converges to the unique fixed point of F .

Proof. Recursively define an increasing sequence of integers $(k_\ell)_{\ell \geq 0}$ as follows. Let $k_0 = 0$ and k_1 be the smallest integer such that

$$\bigcup_{k=0}^{k_1-1} J_k = \{1, \dots, d\},$$

which exists by assumption. Similarly for $\ell \geq 2$, let k_ℓ the smallest integer larger than $k_{\ell-1}$ such that

$$\bigcup_{k=k_{\ell-1}}^{k_\ell-1} J_k = \{1, \dots, d\}.$$

Denote $F_k = F^{|J_k|}$ for all $k \geq 0$ and $G_\ell = F_{k_{\ell+1}-1} \circ \dots \circ F_{k_\ell+1} \circ F_{k_\ell}$ for all $\ell \geq 0$. Then we can apply Proposition 3.3.6 which gives that each map G_ℓ is γ -Lipschitz continuous for $\|\cdot\|_\infty$. Because $x_{k_{\ell+1}} = G_\ell x_{k_\ell}$ for all $\ell \geq 0$, by Theorem 3.3.1, we can write

$$\|x_{k_\ell} - x_*\| \leq \gamma^\ell \|x_0 - x_*\|, \quad \ell \geq 0,$$

where x_* is the unique fixed point of F . Moreover, using the fact that each map F_k ($k \geq 0$) is 1-Lipschitz continuous for $\|\cdot\|_\infty$ and has x_* as fixed point thanks to Propositions 3.3.4 and 3.3.5, we can write for $k > k_\ell$,

$$\begin{aligned} \|x_k - x_*\|_\infty &= \|(F_{k-1} \circ \dots \circ F_{k_\ell})x_{k_\ell} - (F_{k-1} \circ \dots \circ F_{k_\ell})x_*\|_\infty \\ &\leq \|x_{k_\ell} - x_*\|_\infty \leq \gamma^\ell \|x_0 - x_*\|_\infty. \end{aligned}$$

Hence the convergence of x_k to x_* as $k \rightarrow +\infty$. \square

3.4 Asynchronous value iterations

Definition 3.4.1 (Asynchronous value iterations). Let π be a stationary policy.

- (i) A sequence $(v_k)_{k \geq 0}$ in $\mathbb{R}^{\mathcal{S}}$ is an asynchronous state-value iteration for the evaluation of policy π (resp. for control) if there exists a sequence $(\mathcal{S}_k)_{k \geq 0}$ of subsets of \mathcal{S} such that

$$v_{k+1} = B_\pi^{\mathcal{S}_k} v_k, \quad \left(\text{resp. } v_{k+1} = B_*^{\mathcal{S}_k} v_k \right).$$

$(\mathcal{S}_k)_{k \geq 0}$ is then called the sequence of updated states.

- (ii) A sequence $(q_k)_{k \geq 0}$ in $\mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ is an asynchronous state-value iteration for the evaluation of policy π (resp. for control) if there exists a sequence $(\mathcal{Q}_k)_{k \geq 0}$ of subsets of $\mathcal{S} \times \mathcal{A}$ such that

$$q_{k+1} = B_{\pi}^{\mathcal{Q}_k} q_k, \quad \left(\text{resp. } q_{k+1} = B_{*}^{\mathcal{Q}_k} q_k \right).$$

$(\mathcal{Q}_k)_{k \geq 0}$ is then called the sequence of updated state-action pairs.

Proposition 3.4.2 (Convergence of asynchronous value iterations). *Let π be a stationary policy.*

- (i) *Let $(v_k)_{k \geq 0}$ be a state-value iteration for the evaluation of policy π (resp. for control) where each state is updated infinitely. Then, v_k converges to v_{π} (resp. v_{*}) as $k \rightarrow +\infty$.*
- (ii) *Let $(q_k)_{k \geq 0}$ be a action-value iteration for the evaluation of policy π (resp. for control) where each state-action pair is updated infinitely. Then, q_k converges to q_{π} (resp. q_{*}) as $k \rightarrow +\infty$.*

Proof. Follows from Theorem 3.3.7. □

Remark 3.4.3 (Single-component updates).

Chapter 4

Tabular reinforcement learning

Starting from this chapter, we consider MDPs with unknown dynamics, in the sense that the algorithms we are allowed to consider may interact with the environment but do not have access to the transition dynamic p in an explicit form. In particular, the operator D , and therefore the Bellman operators cannot be computed exactly. The image of a value function by a Bellman operator will then be replaced by a stochastic estimator, and the replacement-based updates from the deterministic fixed point iterations will be generalized into averaging-based stochastic ones.

Another consequence of operator D being unavailable is that we cannot determine a greedy policy with respect to a state-value function $v \in \mathbb{R}^{\mathcal{S}}$. For that reason, we will rely on action-value functions instead. An alternative, which will be dealt with later, is *model-based methods* which estimate the transition dynamics through interaction, and which can then derive an approximatively greedy policy with respect to a state-value function.

This chapter focuses on *tabular* methods, which work by manipulating whole action-value functions $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ and whole stationary policies $\pi \in \Delta(\mathcal{A})^{\mathcal{S}}$. In the following chapters, we will study methods that approximate action-value functions and/or policies with parametric families for better scalability.

4.1 Stochastic asynchronous fixed point iterations

The asynchronous fixed-point iterations in \mathbb{R}^d ($d \geq 1$) from Section 3.3 can be written as

$$x_{t+1} = (1 - \mathbb{1}_{J_k}) \otimes x_t + \mathbb{1}_{J_k} \otimes Fx_t, \quad k \geq 0,$$

where \otimes denotes component-wise multiplication, J_k is the set of components that are updated at iteration k , and $\mathbb{1}_{J_k}$ the corresponding indicator vec-

tor, meaning for all $1 \leq j \leq d$, $(\mathbb{1}_{J_k})_j = \mathbb{1}_{\{j \in J_k\}}$. This expression easily generalises into an averaging procedure of the form

$$x_{t+1} = (1 - \alpha_k) \otimes x_t + \alpha_k \otimes \hat{f}_k, \quad k \geq 0,$$

where α_k is a vector in $[0, 1]^d$, which is sometimes called a *stochastic approximation* procedure and presented as a method which computes an approximate zero of operator $F - \text{Id}$, if \hat{f}_k , conditionnaly on x_k is an unbiased estimator of Fx_k . In addition to being a stochastic generalization of fixed-point iterations, it can also be seen as an extension of basic mean estimation. If $(Z_k)_{k \geq 1}$ are i.i.d. random vectors with common mean $\mu \in \mathbb{R}^d$, then μ is the unique fixed point of operator $x \mapsto \mu$, and procedure $x_{k+1} = (1 - \frac{1}{k+1})x_k + \frac{1}{k+1}z_k$ is equivalent to simple averaging $x_{k+1} = \frac{1}{k+1} \sum_{\ell=0}^k z_\ell$.

We give without proof the following convergence guarantee.

Theorem 4.1.1 (Tsitsiklis, 1994). *Let $d \geq 1$, $\gamma \in (0, 1)$, $F : \mathbb{R}^d \rightarrow \mathbb{R}^d$ a γ -Lipschitz continous map with respect to $\|\cdot\|_\infty$, $(x_k)_{k \geq 0}$, $(\alpha_k)_{k \geq 0}$ and $(\hat{f}_k)_{k \geq 0}$ sequences of random vectors in \mathbb{R}^d and $(\mathcal{F}_k)_{k \geq 0}$ a filtration. We assume that*

- (i) $x_{k+1} = (1 - \alpha_k) \otimes x_k + \alpha_k \otimes \hat{f}_k$, for all $k \geq 0$,
- (ii) x_k and α_k are \mathcal{F}_k -measurable, for all $k \geq 0$,
- (iii) there exists $c_1, c_2 \geq 0$ such that for all $k \geq 0$ and $1 \leq j \leq d$,

$$\alpha_{k,j} \neq 0 \implies \begin{cases} \mathbb{E}[\hat{f}_{k,j} | \mathcal{F}_k] = (Fx_k)_j, \\ \text{Var}(\hat{f}_{k,j} | \mathcal{F}_k) \leq c_1 + c_2 \|x_k\|_\infty^2, \end{cases}$$

- (iv) for all $1 \leq j \leq d$, almost-surely, $(\alpha_{k,j})_{k \geq 0}$ is a nonnegative sequence and

$$\sum_{k=0}^{+\infty} \alpha_{k,j} = +\infty \quad \text{and} \quad \sum_{k=0}^{+\infty} \alpha_{k,j}^2 < +\infty.$$

Then, $(x_k)_{k \geq 0}$ converges almost-surely to the unique fixed point of F .

4.2 Stochastic estimators of Bellman operators

We know from Proposition 2.1.3 that Bellman expectation operators can be written as expectations. We derive similar expressions for $(B_\pi^{(V)})^T$ and $(B_\pi^{(Q)})^T$ (for $T \geq 1$) that involve an expectation of the discounted sum of rewards up to time T plus an approximation of the remaining rewards. We then also derive a similar expression for $B_*^{(Q)}$. Those will be used to construct stochastic estimators of Bellman operators.

Proposition 4.2.1. *Let $T \geq 1$, $v \in \mathbb{R}^{\mathcal{S}}$, $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$, $s \in \mathcal{S}$ and $a \in \mathcal{A}$.*

$$(i) \quad (B_{\pi}^T v)(s) = \mathbb{E}_{s,\pi} \left[\sum_{t=1}^T \gamma^{t-1} R_t + \gamma^T v(S_T) \right].$$

$$(ii) \quad (B_{\pi}^T q)(s, a) = \mathbb{E}_{s,a,\pi} \left[\sum_{t=1}^T \gamma^{t-1} R_t + \gamma^T q(S_T, A_T) \right].$$

$$(iii) \quad (B_{*}^T v)(s) = \max_{\pi \in \Pi_{0,d}} \mathbb{E}_{s,\pi} \left[\sum_{t=1}^T \gamma^{t-1} R_t + \gamma^T v(S_T) \right].$$

$$(iv) \quad (B_{*}^T q)(s, a) = \max_{\pi \in \Pi_{0,d}} \mathbb{E}_{s,a,\pi} \left[\sum_{t=1}^T \gamma^{t-1} R_t + \gamma^T q(S_T, A_T) \right].$$

Proof. We proceed by induction. Property (i) is true for $T = 1$ by Proposition 2.1.3. For $T \geq 2$, let $(S'_0, A'_0, R'_0, \dots) \sim \mathbb{P}_{s,\pi}$ and we write

$$\begin{aligned} (B_{\pi}^T v)(s) &= (B_{\pi}^{T-1} B_{\pi} v)(s) = \mathbb{E} \left[\sum_{t=1}^{T-1} \gamma^{t-1} R'_t + \gamma^{T-1} (B_{\pi} v)(S'_{T-1}) \right] \\ &= \mathbb{E} \left[\sum_{t=1}^{T-1} \gamma^{t-1} R'_t + \gamma^{T-1} \mathbb{E}_{S'_{T-1}, \pi} [R_1 + \gamma v(S_1)] \right] \\ &= \mathbb{E} \left[\sum_{t=1}^{T-1} \gamma^{T-1} R'_t + \gamma^{T-1} \mathbb{E} [R'_T + \gamma v(S'_T) \mid S'_{T-1}] \right] \\ &= \mathbb{E} \left[\sum_{t=1}^T R_t + \gamma^T v(S'_T) \right], \end{aligned}$$

where we used the Markov property from Proposition 1.3.4 to get the third line. This proves property (i). Property (ii) is proved similarly. Then, properties (iii) and (iv) immediatly follow from Proposition 2.1.7. \square

Regarding Bellman optimality operators, the above expressions for $(B_{*}^{(V)})^T$ and $(B_{*}^{(V)})^T$ are not *a priori* written as expectations, but as a maximums of expectations, and therefore do not yield straightforward constructions for unbiased stochastic estimators. In the special case of $B_{*}^{(Q)}$ however (with $T = 1$), the following corollary does give such an expression.

Corollary 4.2.2. *For $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ and $(s, a) \in \mathcal{S} \times \mathcal{A}$,*

$$(B_{*} q)(s, a) = \mathbb{E}_{(R, S') \sim p(\cdot \mid s, a)} \left[R + \gamma \max_{a \in \mathcal{A}} q(S', a) \right].$$

Proof. Proposition 4.2.1 gives

$$(B_*q)(s, a) = \max_{\pi \in \Pi_{0,d}} \mathbb{E}_{s,a,\pi} [R_1 + \gamma q(S_1, A_1)].$$

Let $\pi \in \Pi_{0,d}$ and $(S'_0, A'_0, R'_1, \dots) \sim \mathbb{P}_{s,a,\pi}$. Then,

$$\begin{aligned} \mathbb{E}_{s,a,\pi} [R_1 + \gamma q(S_1, A_1)] &= \mathbb{E} [R'_1 + \gamma q(S'_1, A'_1)] \\ &\leq \mathbb{E} \left[R'_1 + \gamma \max_{a \in \mathcal{A}} q(S'_1, a) \right] \\ &= \mathbb{E} [R'_1 + \gamma q(S'_1, \pi_g[q](S'_1))] \\ &= \mathbb{E}_{s,a,\pi_g} [R_1 + \gamma q(S_1, A_1)]. \end{aligned}$$

Therefore, taking the maximum over $\pi \in \Pi_{0,d}$ and because $\pi_g[q] \in \Pi_{0,d}$ by definition of greedy policies, π_g attains the maximum and

$$\begin{aligned} (B_*q)(s, a) &= \mathbb{E}_{s,a,\pi_g} [R_1 + \gamma q(S_1, A_1)] \\ &= \mathbb{E} \left[R'_1 + \gamma \max_{a \in \mathcal{A}} q(S'_1, a) \right] \\ &= \mathbb{E}_{(R,S') \sim p(\cdot | s, a)} \left[R + \gamma \max_{a \in \mathcal{A}} q(S', a) \right], \end{aligned}$$

where the last equality stands because $(R'_1, S'_1) \sim p(\cdot | s, a)$ as an immediate consequence of the definition of $\mathbb{P}_{s,a,\pi}$. \square

Definition 4.2.3. For $T \geq 1$, we call *history of length T^+* a tuple of the form:

$$(S_0, A_0, R_1, \dots, S_{T-1}, A_{T-1}, R_T, S_T, A_T) \in (\mathcal{S} \times \mathcal{A} \times \mathcal{R})^{T-1} \times \mathcal{S} \times \mathcal{A}.$$

We denote $\mathcal{H}^{(T^+)}$ the set of histories of length T^+ .

Definition 4.2.4. For $T \geq 1$, $s \in \mathcal{S}$ and $a \in \mathcal{A}$, and $\pi \in \Pi_0$, we denote $\mathbb{P}_{s,a,\pi}^{(T^+)}$ the probability distribution on $\mathcal{H}^{(T^+)}$ induced by $\mathbb{P}_{s,a,\pi}$. By convention and for consistency, we denote $\mathcal{H}^{(\infty+)} = \mathcal{H}^{(\infty)}$ and $\mathbb{P}_{s,a,\pi}^{(\infty+)} = \mathbb{P}_{s,a,\pi}$.

For $T \geq 1$, $H = (S_0, A_0, R_1, \dots, S_T, A_T) \in \mathcal{H}^{(T^+)}$ and $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$, we denote

$$(\hat{B}^T q)(H) = \sum_{t=1}^T \gamma^{t-1} R_t + \gamma^T q(S_T, A_T),$$

and if $H \sim \mathbb{P}_{s,a,\pi}^{(T^+)}$ for some $(s, a) \in \mathcal{S} \times \mathcal{A}$ and $\pi \in \Pi_0$, according to Proposition 4.2.1, $(\hat{B}^T q)(H)$ is an unbiased estimator of $(B_\pi^T q)(s, a)$.

For consistency, we also denote for $H = (S_0, A_0, R_1, \dots) \in \mathcal{H}^{(\infty)}$

$$(\hat{B}^\infty q)(H) = \sum_{t=1}^{+\infty} \gamma^{t-1} R_t,$$

which does not depend on q , and which is an unbiased estimator of $q_\pi = \lim_{T \rightarrow +\infty} B_\pi^T q$ by definition of the latter (as soon as $H^{(\infty)} \sim \mathbb{P}_{s,a,\pi}$).

For $(R, S') \in \mathcal{R} \times \mathcal{S}$, we denote

$$(\hat{B}_* q)(R, S') = R + \gamma \max_{a \in \mathcal{A}} q(S', a),$$

and if $(R, S') \sim p(\cdot | s, a)$ for some $(s, a) \in \mathcal{S} \times \mathcal{A}$, then $(\hat{B}_* q)(R, S')$ is an unbiased estimator of $(B_* q)(s, a)$ thanks to Corollary 4.2.2.

The following proposition establishes upper bounds on the variance of those estimators.

Proposition 4.2.5. *Let $T \geq 0$, $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ and $(s, a) \in \mathcal{S} \times \mathcal{A}$. Denote $M_{\mathcal{R}} = \sup_{r \in \mathcal{R}} |r|$.*

(i) *If $H \sim \mathbb{P}_{s,a,\pi}^{(T+)}$, then*

$$\text{Var} \left((\hat{B}^T q)(H) \right) \leq \frac{4M_{\mathcal{R}}^2}{1-\gamma} + \frac{5}{1-\gamma} \|q\|_\infty^2.$$

(ii) *If $(R, S') \sim p(\cdot | s, a)$, then*

$$\text{Var} \left((\hat{B}_* q)(R, S') \right) \leq 2M_{\mathcal{R}}^2 + 2\gamma^2 \|q\|_\infty^2.$$

Proof. Denote $H = (S_0, A_0, R_1, \dots)$. Note that for all $1 \leq t \leq T$,

$$\text{Var}(R_t) \leq \mathbb{E}[R_t^2] \leq M_{\mathcal{R}}^2,$$

and

$$\text{Var}(q(S_T, A_T)) \leq \mathbb{E}[q(S_T, A_T)^2] \leq \|q\|_\infty^2,$$

and similarly $\text{Var}(\max_{a \in \mathcal{A}} q(S, a)) \leq \|q\|_\infty^2$. Then, using formula

$$\text{Var} \left(\sum_{i=1}^n X_i \right) = \sum_{i=1}^n \text{Var} X_i + 2 \sum_{i < j} \text{Cov}(X_i, X_j)$$

and inequalities

$$\text{Cov}(X, Y) \leq \sqrt{(\text{Var} X)(\text{Var} Y)} \leq 2 \text{Var} X + 2 \text{Var} Y,$$

we write

$$\begin{aligned}
\text{Var} \left((\hat{B}^T q)(H) \right) &= \text{Var} \left(\sum_{t=1}^T \gamma^{t-1} R_t + \gamma^T q(S_T, A_T) \right) \\
&= \sum_{t=1}^T \text{Var} (\gamma^{t-1} R_t) + \text{Var} (\gamma^T q(S_T, A_T)) + \\
&\quad + 2 \sum_{1 \leq t < t' \leq T} \text{Cov} (\gamma^{t-1} R_t, \gamma^{t'-1} R_{t'}) \\
&\quad + 2 \sum_{t=1}^T \text{Cov} (\gamma^{t-1} R_t, \gamma^T q(S_T, A_T)) \\
&\leq M_{\mathcal{R}}^2 \sum_{t=1}^T \gamma^{2t-2} + \gamma^{2T} \|q\|_{\infty}^2 + 2M_{\mathcal{R}}^2 \sum_{1 \leq t < t' \leq T} \gamma^{t+t'-2} \\
&\quad + 4 \sum_{t=1}^T \gamma^{T+t-1} (M_{\mathcal{R}}^2 + \|q\|_{\infty}^2).
\end{aligned}$$

(i) follows by simplifying. We now turn to (ii):

$$\begin{aligned}
\text{Var} \left((\hat{B}_* q)(R, S') \right) &= \text{Var} \left(R + \gamma \max_{a \in \mathcal{A}} (S', a) \right) \\
&\leq 2 \text{Var} R + 2\gamma^2 \text{Var} \left(\max_{a \in \mathcal{A}} q(S', a) \right) \\
&\leq 2M_{\mathcal{R}}^2 + 2\gamma^2 \|q\|_{\infty}^2.
\end{aligned}$$

□

4.3 Policy evaluation

In this section, we study methods that compute the action-value function q_{π} of a stationary policy π by combining stochastic synchronous fixed point iteration from Section 4.1 and estimators of Bellman expectation operator $B_{\pi}^{(Q)}$ from Section 4.2.

Let us first give an informal description. Let $T \in \{1, 2, \dots\} \cup \{+\infty\}$. For each $k \geq 0$, we choose a state-action pair $(S_{0,k}, A_{0,k})$, possibly at random as a function of previous observations. Starting from initial state $S_{0,k}$ and action $A_{0,k}$, we generate a history of length T^+ by using policy π :

$$H_k = (S_{0,k}, A_{0,k}, R_{1,k}, \dots, S_{T,k}, A_{T,k}) \mid S_{0,k}, A_{0,k} \sim \mathbb{P}_{S_{0,k}, A_{0,k}, \pi}^{(T^+)}$$

We asynchronously update the component of the action-value function cor-

responding to $(S_{0,k}, A_{0,k})$ so that

$$q_{k+1}(S_{0,k}, A_{0,k}) = \frac{\sum_{\ell=0}^k \mathbb{1} \{(S_{0,\ell}, A_{0,\ell}) = (S_{0,k}, A_{0,k})\} \times \hat{B}^T(H_k)}{\sum_{\ell=0}^k \mathbb{1} \{(S_{0,\ell}, A_{0,\ell}) = (S_{0,k}, A_{0,k})\}},$$

and $q_{k+1}(s, a) = q_k(s, a)$ for $(s, a) \neq (S_{0,k}, A_{0,k})$, which can be equivalently written as

$$q_{k+1} = (1 - \alpha_k) \otimes q_k + \hat{B}^T(H_k) \alpha_k,$$

where

$$\alpha_k = \left(\frac{\mathbb{1} \{S_{0,k} = s, A_{0,k} = a\}}{\sum_{\ell=0}^k \mathbb{1} \{S_{0,\ell} = s, A_{0,\ell} = a\}} \right)_{(s,a) \in \mathcal{S} \times \mathcal{A}}.$$

- The case $T = 1$ is called *Temporal Difference (TD)*.
- The case $1 < T < +\infty$ is called *T-step Temporal Difference*.
- The case $T = +\infty$ is called *on-policy Monte-Carlo policy evaluation*, and cannot be implemented in general, because they require to generate histories of infinite length. They may however be implemented in cases where either the policy at hand and/or the assumptions on the MDP force the rewards to be nonzero only for a finite number of steps.

Proposition 4.3.1. *Let $T \in \{1, 2, \dots\} \cup \{+\infty\}$, π a stationary policy, $(H_k)_{k \geq 0}$ a family of random histories of length T^+ denoted*

$$H_k = (S_{0,k}, A_{0,k}, R_{1,k}, \dots, S_{T,k}, A_{T,k}), \quad k \geq 0.$$

Consider filtration $\mathcal{F} = (\mathcal{F}_k)_{k \geq 0}$ where

$$\mathcal{F}_k = \sigma(H_1, \dots, H_{k-1}, S_{0,k}, A_{0,k}), \quad k \geq 0.$$

We assume that:

- (i) *for all $k \geq 0$, the law of random history H_k conditionnaly on \mathcal{F}_k is $\mathbb{P}_{S_{0,k}, A_{0,k}, \pi}$,*
- (ii) *$(q_k)_{k \geq 0}$ is a random sequence in $\mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ satisfying for all $k \geq 0$, almost-surely,*

$$q_{k+1} = (1 - \alpha_k) \otimes q_k + \hat{B}^T(H_k) \alpha_k,$$

where,

$$\alpha_k = \left(\frac{\mathbb{1} \{S_{0,k} = s, A_{0,k} = a\}}{\sum_{\ell=0}^k \mathbb{1} \{S_{0,\ell} = s, A_{0,\ell} = a\}} \right)_{(s,a) \in \mathcal{S} \times \mathcal{A}},$$

(iii) almost-surely, for all $(s, a) \in \mathcal{S} \times \mathcal{A}$,

$$\sum_{k=0}^{+\infty} \mathbb{1} \{S_{0,k} = s, A_{0,k} = a\} = +\infty.$$

Then, q_k converges almost-surely to q_π as $k \rightarrow +\infty$.

Proof. We can see that above satisfy the assumptions of Theorem 4.1.1 with operator $(B_\pi^{(Q)})^T$ (where in the case $T = +\infty$, $(B_\pi^{(Q)})^\infty$ corresponds to the constant map $q \mapsto q_\pi$), which is indeed γ -Lipschitz thanks to Proposition 2.2.4 and which gives the almost-sure convergence of q_k to its unique fixed point q_π .

Indeed, the assumptions on the stochastic estimators are given by Propositions 4.2.1 & 4.2.5 and Corollary 4.2.2.

Regarding measurability, for $k \geq 0$, it follows from the definition of α_k that it is \mathcal{F}_k -measurable. We then prove by an immediate induction that q_k is \mathcal{F}_k -measurable.

Finally, for all $(s, a) \in \mathcal{S} \times \mathcal{A}$,

$$\sum_{k=0}^{+\infty} \alpha_k(s, a) = \sum_{k=0}^{+\infty} \frac{\mathbb{1} \{S_{0,k} = s, A_{0,k} = a\}}{\sum_{\ell=0}^k \mathbb{1} \{S_{0,\ell} = s, A_{0,\ell} = a\}} = \sum_{m=1}^{+\infty} \frac{1}{m} = +\infty,$$

and

$$\sum_{k=0}^{+\infty} \alpha_k(s, a)^2 = \sum_{k=0}^{+\infty} \frac{\mathbb{1} \{S_{0,k} = s, A_{0,k} = a\}}{(\sum_{\ell=0}^k \mathbb{1} \{S_{0,\ell} = s, A_{0,\ell} = a\})^2} = \sum_{m=1}^{+\infty} \frac{1}{m^2} < +\infty.$$

□

4.4 Q-learning

We now turn to Q-learning, which is one of the core reinforcement learning algorithms for control. It combines the stochastic fixed point iterations from Tsitsiklis' Theorem 4.1.1 with the stochastic estimator of Bellman optimality operator from Corollary 4.2.2.

It can be informally described as follows. For each $k \geq 0$, we choose a state-action pair (S_k, A_k) , possibly at random as a function of previous observations. Starting from initial state S_k and action A_k , we generate a history of length 1^+ , meaning a reward and a next state given by the MDPs dynamic (which needs not be known explicitly):

$$H_k = (S_k, A_k, R_k, S'_k) \mid S_k, A_k \sim p(\cdot \mid S_k, A_k).$$

We asynchronously update the component of the action-value function corresponding to (S_k, A_k) so that

$$q_{k+1}(S_k, A_k) = \frac{\sum_{\ell=0}^k \mathbb{1} \{(S_\ell, A_\ell) = (S_k, A_k)\} \times \hat{B}_*(R_k, S'_k)}{\sum_{\ell=0}^k \mathbb{1} \{(S_\ell, A_\ell) = (S_k, A_k)\}},$$

and $q_{k+1}(s, a) = q_k(s, a)$ for $(s, a) \neq (S_k, A_k)$, which can be equivalently written as

$$q_{k+1} = (1 - \alpha_k) \otimes q_k + \hat{B}_*(R_k, S'_k) \alpha_k,$$

where

$$\alpha_k = \left(\frac{\mathbb{1} \{S_{0,k} = s, A_{0,k} = a\}}{\sum_{\ell=0}^k \mathbb{1} \{S_{0,\ell} = s, A_{0,\ell} = a\}} \right)_{(s,a) \in \mathcal{S} \times \mathcal{A}}.$$

Q-learning is said to be an *off-policy* method, because although a stationary policy π may be used to generate histories (so that $A_k | S_k \sim \pi(S_k)$ and $S_{k+1} = S'_k$ for all $k \geq 0$), that policy may very well be quite different from the one that is being learnt.

Proposition 4.4.1. *Let $(H_k)_{k \geq 0}$ be a family of random histories of length 1^+ denoted $H_k = (S_k, A_k, R_k, S'_k)$. Consider filtration $\mathcal{F} = (\mathcal{F}_k)_{k \geq 0}$ where*

$$\mathcal{F}_k = \sigma(H_0, \dots, H_{k-1}, S_k, A_k), \quad k \geq 0.$$

We assume that

- (i) *for all $k \geq 0$, the law of (R_k, S'_k) conditionnaly on \mathcal{F}_k is $p(\cdot | S_k, A_k)$,*
- (ii) *$(q_k)_{k \geq 0}$ is a random sequence in $\mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ satisfying, for all $k \geq 0$, almost-surely,*

$$q_{k+1} = (1 - \alpha_k) \otimes q_k + \hat{B}_*(R_k, S'_k) \alpha_k, \quad k \geq 0,$$

where

$$\alpha_k = \left(\frac{\mathbb{1} \{S_k = s, A_k = a\}}{\sum_{\ell=0}^k \mathbb{1} \{S_\ell = s, A_\ell = a\}} \right)_{(s,a) \in \mathcal{S} \times \mathcal{A}},$$

- (iii) *almost-surely, for all $(s, a) \in \mathcal{S} \times \mathcal{A}$,*

$$\sum_{k=0}^{+\infty} \mathbb{1} \{S_k = s, A_k = a\} = +\infty.$$

Then, q_k converges almost-surely to q_ as $k \rightarrow +\infty$.*

Proof. Similar to Proposition 4.3.1. □

Remark 4.4.2 (On exploration). The last assumption of the above proposition is extremely important and there are several ways to ensure that all state-action pairs are updated infinitely often. One possibility is to draw each pair (S_k, A_k) e.g. uniformly from $\mathcal{S} \times \mathcal{A}$. This is not always possible, as the state of the environment may not be freely chosen: states may be accessible only through interaction starting from some initial state. In that case, S_k can only be chosen as given by the last interaction, meaning $S_k = S'_{k-1}$. Another possibility is to follow a policy which at all states ensures that each action is selected with positive probability, and then hope that this would yield an infinite exploration of all state-action pairs.

4.5 Policy iteration

Definition 4.5.1 (Exploring ε -greedy policies). Let $\varepsilon \geq 0$. The *exploring ε -greedy policy* with respect to an action-value function $q \in \mathbb{R}^{\mathcal{S} \times \mathcal{A}}$ is the stationary policy denoted $\pi_{g,\varepsilon}[q]$ defined as:

$$\pi_{g,\varepsilon}(a|s) = \begin{cases} \frac{1-\varepsilon}{|\text{Arg max}_{a' \in \mathcal{A}} q(s, a')|} + \frac{\varepsilon}{|\mathcal{A}|}, & \text{if } a \in \text{Arg max}_{a' \in \mathcal{A}} q(s, a') \\ \frac{\varepsilon}{|\mathcal{A}|} & \text{otherwise.} \end{cases}$$

Remark 4.5.2. The above (restrictive) definition uniquely defines a policy. In the case $\varepsilon = 0$, the above may not be a greedy policy, as the latter are deterministic by definition.

We now describe a family of stochastic generalized policy iteration methods, which like their deterministic counterpart, alternate between an approximate policy evaluation step and a policy improvement step.

Let $T \in \{1, 2, \dots\} \cup \{+\infty\}$ and $(\varepsilon_k)_{k \geq 0}$ be a positive sequence. For each $k \geq 0$, we first compute $\pi_k = \pi_{g,\varepsilon_k}[q_k]$. Then, we choose a state-action pair $(S_{0,k}, A_{0,k})$, possibly at random and as a function of previous observations. Starting from initial state $S_{0,k}$ and action $A_{0,k}$, we generate a history of length T^+ using policy π_k :

$$H_k = (S_{0,k}, A_{0,k}, R_{1,k}, \dots, S_{T,k}, A_{T,k}) \mid S_{0,k}, A_{0,k} \sim \mathbb{P}_{S_{0,k}, A_{0,k}, \pi_k}.$$

The action-value function is then asynchronously updated as:

$$q_{k+1} = (1 - \alpha_k) \otimes q_k + \hat{B}^T(H_k) \alpha_k,$$

$$\alpha_k = \left(\frac{\mathbb{1}\{S_{0,k} = s, A_{0,k} = a\}}{\sum_{\ell=0}^k \mathbb{1}\{S_{0,\ell} = s, A_{0,\ell} = a\}} \right)_{(s,a) \in \mathcal{S} \times \mathcal{A}}.$$

- In the case $T = 1$, the corresponding algorithm is called *SARSA* (where the letters correspond to the use of variables $S_{0,k}, A_{0,k}, R_{1,k}, S_{1,k}, A_{1,k}$ when computing estimator $\hat{B}(H_k)$).

- In the case $1 < T < +\infty$, the algorithm is called *T-step SARSA*.
- In the case $T = +\infty$, the algorithm is called *on-policy Monte-Carlo control*.

The above algorithms are said to be *on-policy* because the policy used to generate the histories are close to the policy that is being learnt.