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Markov Chain Monte Carlo - Theory and practical applications

A crash course in Monte Carlo methods by Markov chains



Introduction

This course is given at the Master M2 DS. The schedule is roughly the following:

- ▶ Chapter 1-2. Lecture, 1.5H. Tutorial: 2H.
- ▶ Chapter 2-3. Lecture, 1.5H. Tutorial: 2H.
- ▶ Chapter 3-4. Lecture, 1.5H. Tutorial: 2H.
- ▶ Chapter 4-5. Lecture, 1.5H. Tutorial: 2H.
- ▶ Chapter 5-6. Lecture, 1.5H. Tutorial: 2H.
- ▶ Chapter 6. Lecture, 1.5H. Tutorial: 2H.

Numerical illustrations through Jupyter Notebook were given during the course and the source can be run directly in a *colaboratory google site* by following this link.

Since we focus here on Markov Chains Monte Carlo algorithms, we only give the flavor of Markov chains. It can be a bit frustrating to some of you and we strongly encourage the most curious readers in Markov chains to consult one of the books

- *Markov Chains and Stochastic Stability* S. Meyn and R. Tweedie. Springer, 2005 (2nd edition).
- *Markov Chains* by R. Douc, E. Moulines, P. Priouret and P. Soulier. Springer, jan. 2019.

Interested readers on Monte Carlo techniques can find some inspiration in

- *Monte Carlo Statistical Methods* by G. Casella and C. Robert. Springer, 2004.

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Notation

We start with some notation. In what follows,

- i.i.d means independent and identically distributed.
- r.v. means random variables.
- for $r, s \in \mathbb{N}$ such that $r \leq s$, we write $[r : s] = \{r, r + 1, \dots, s\}$,
- $X \perp\!\!\!\perp Y$ means X and Y are independent random variables,
- $X \stackrel{\mathcal{L}}{=} Y$ means X and Y have the same law.
- $\liminf_n a_n = \lim_{n \rightarrow \infty} (\inf_{k \geq n} a_k)$ and similarly, $\limsup_n a_n = \lim_{n \rightarrow \infty} (\sup_{k \geq n} a_k)$. Moreover, $\lim_n a_n$ exists if and only if $\liminf_n a_n = \limsup_n a_n$.
- for any $a \in \mathbb{R}$, $a^+ = \max(a, 0)$ and $a^- = \max(-a, 0) = -\min(a, 0)$ and we have $|a| = a^+ + a^-$ and $a = a^+ - a^-$.

Moreover, the following notions of convergence for random variables is used throughout these lecture notes.

► $X_n \xrightarrow{\mathcal{L}_F} X$ means *convergence in distribution* (or "convergence en loi" in French). It is equivalent to any of the following statements.

- (a) for all bounded continuous functions h , we have $\lim_n \mathbb{E}[h(X_n)] = \mathbb{E}[h(X)]$.
- (b) for all $A \in \mathcal{B}(\mathbb{R})$ such that $\mathbb{P}(X \in \partial A) = 0$, we have $\lim_n \mathbb{P}(X_n \in A) = \mathbb{P}(X \in A)$.
- (c) for all $x \in \mathbb{R}$ such that $\mathbb{P}(X = x) = 0$, we have $\lim_n \mathbb{P}(X_n \leq x) = \mathbb{P}(X \leq x)$.
- (d) for all $u \in \mathbb{R}$, we have $\lim_n \mathbb{E}[e^{iuX_n}] = \mathbb{E}[e^{iuX}]$

In (b), the notation ∂A means the frontier of A , that is, the set of points x such that in any neighborhood of x , there are an infinite number of distinct points of A and an infinite number of points in A^c . By abuse of terminology, we may also say that X_n **weakly converges to** X instead of saying the distribution of X_n converges weakly to the distribution of X .

► $X_n \xrightarrow{\mathbb{P}\text{-prob}} X$ means *convergence in probability*: for all $\epsilon > 0$,

$$\lim_{n \rightarrow \infty} \mathbb{P}(|X_n - X| > \epsilon) = 0.$$

► $X_n \xrightarrow{\mathbb{P}\text{-a.s.}} X$ means *almost sure convergence*:

$$\mathbb{P}\left(\lim_{n \rightarrow \infty} X_n = X\right) = 1.$$

Almost sure convergence implies convergence in probability. We recall the following properties.

- (i) If $X_n \xrightarrow{\mathcal{L}_F} X$ then for all continuous functions f , $f(X_n) \xrightarrow{\mathcal{L}_F} f(X)$. Note that this property holds, when f is continuous (and not necessarily bounded), for example $f(u) = u^2$ so that $X_n^2 \xrightarrow{\mathcal{L}_F} X^2$.
- (ii) **The Slutsky Lemma** If $X_n \xrightarrow{\mathbb{P}\text{-prob}} c$ where c is a constant and if $Y_n \xrightarrow{\mathcal{L}_F} Y$, then $(X_n, Y_n) \xrightarrow{\mathcal{L}_F} (c, Y)$ that is for all continuous functions f , $f(X_n, Y_n) \xrightarrow{\mathcal{L}_F} f(c, Y)$.
- (iii) $X \sim \mathcal{N}(0, 1)$ iff for all $u \geq 0$, $\mathbb{E}[e^{iuX}] = e^{-u^2/2}$. Moreover, $X \sim \mathcal{N}(\mu, \sigma^2)$ iff for all $u \geq 0$, $\mathbb{E}[e^{iuX}] = e^{-u^2 \text{var} X / 2 + iu \mathbb{E}[X]}$ and in that case, $\sigma^2 = \text{var} X$ and $\mu = \mathbb{E}(X)$.
- (iv) Let c be a constant. Then, $X_n \xrightarrow{\mathbb{P}\text{-prob}} c$ if and only if $X_n \xrightarrow{\mathcal{L}_F} c$ (in words, convergence in probability to a **constant** is equivalent to convergence in distribution to this **constant**)

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Chapter 1

Basics in Markov chains.

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Keywords: Markov chains, Markov property, Metropolis Hastings, canonical space.

These short lecture notes introduce very basic tools in the Markov Chain by Monte-Carlo (MCMC) theory. We only focus on the most fundamental properties that will be useful for our understanding of Metropolis-Hastings (MH) algorithms. Let us start with a gentle and smooth introduction to Markov chains.

1.1 Main notation

To start off on the right foot, we introduce the main notation. Let (X, \mathcal{X}) be a measurable space,

- $M_+(X)$ is the set of (non-negative) measures on (X, \mathcal{X}) ,
- $M_1(X)$ is the set of probability measures on (X, \mathcal{X}) ,
- $F(X)$ is the set of real-valued measurable functions f on X and $F_+(X)$ the set of non-negative measurable functions on X ,
- If $k \leq \ell$,
 - $u_{k:\ell}$ means (u_k, \dots, u_ℓ)
 - $u_{k:\infty}$ means $(u_{k+\ell})_{\ell \in \mathbb{N}}$

Other notation will be introduced progressively.

1.2 Definitions

We first describe a Markov kernel, which will then be fundamental for the definition of a Markov chain. In all the course, we consider (X, \mathcal{X}) a measurable space.

Definition 1.1. We say that $P : \mathsf{X} \times \mathcal{X} \rightarrow \mathbb{R}^+$ is a Markov kernel, if for all $(x, A) \in \mathsf{X} \times \mathcal{X}$,

- $\mathsf{X} \ni y \mapsto P(y, A)$ is $\mathcal{X}/\mathcal{B}(\mathbb{R}^+)$ measurable,
- $\mathcal{X} \ni B \mapsto P(x, B)$ is a probability measure on $(\mathsf{X}, \mathcal{X})$.

In words, for all $(x, A) \in \mathsf{X} \times \mathcal{X}$, as a function of the first component only, $P(\cdot, A)$ is measurable and as a function of the second component only, $P(x, \cdot)$ is a probability measure. In particular, $P(x, \mathsf{X}) = 1$ for all $x \in \mathsf{X}$. Since $P(x, \cdot)$ is a measure, we also use the infinitesimal notation: $P(x, dy)$. For example, $P(x, A) = \int_{\mathsf{X}} \mathbf{1}_A(y) P(x, dy) = \int_A P(x, dy)$.

In almost all the course, Markov kernels P allows to move a point x from a measurable space $(\mathsf{X}, \mathcal{X})$ to another point on the same measurable space, that is, P is defined on $\mathsf{X} \times \mathcal{X}$ (where \mathcal{X} is a σ -field on X) but we can more generally define Markov kernel from a measurable space $(\mathsf{X}, \mathcal{X})$ to another measurable space $(\mathsf{Y}, \mathcal{Y})$. In such case, P will be a Markov kernel on $\mathsf{X} \times \mathcal{Y}$.

We can now move on to the definition of a Markov chain.

Definition 1.2. Let $\{X_k : k \in \mathbb{N}\}$ be a sequence of random variables on the same probability space $(\Omega, \mathcal{G}, \mathbb{P})$ and taking values on X , we say that $\{X_k : k \in \mathbb{N}\}$ is a Markov chain with Markov kernel P and initial distribution $\nu \in \mathsf{M}_1(\mathsf{X})$ if and only if

- (i) for all $(k, A) \in \mathbb{N} \times \mathcal{X}$, we have $\mathbb{P}(X_{k+1} \in A | X_{0:k}) = P(X_k, A)$, \mathbb{P} -a.s.
- (ii) $\mathbb{P}(X_0 \in A) = \nu(A)$.

Note that in the definition we consider $\mathbb{P}(X_{k+1} \in A | X_{0:k})$, that is, the conditional probability is with respect to the sigma-field $\sigma(X_{0:k})$. We can actually replace $\sigma(X_{0:k})$ by \mathcal{F}_k as soon as we know that $(X_k)_{k \geq 0}$ is $(\mathcal{F}_k)_{k \geq 0}$ -adapted...

What does it mean exactly? Well, recall that if $\{\mathcal{F}_k : k \in \mathbb{N}\}$ is a sequence of embedded sigma-fields on X (that is, $\mathcal{F}_k \subset \mathcal{F}_{k+1}$ for all k), then $\{\mathcal{F}_k : k \in \mathbb{N}\}$ is called a **filtration** on X and we say that $(X_k)_{k \geq 0}$ is $(\mathcal{F}_k)_{k \geq 0}$ -adapted if X_k is $\mathcal{G}/\mathcal{F}_k$ -measurable for all $k \in \mathbb{N}$. Of course, the most natural filtration for $\{X_k : k \in \mathbb{N}\}$ is indeed $\mathcal{F}_k = \sigma(X_{0:k})$ and unsurprisingly, we call it the **natural filtration**. But other possibilities exist, where \mathcal{F}_k is enlarged to include some other variables alongside with $X_{0:k}$. For example, let $\{Y_k : k \in \mathbb{N}\}$ be any other sequence of random variables on $(\Omega, \mathcal{G}, \mathbb{P})$ and taking values in X (we don't assume anything on the relation between the (X_k) and the (Y_k)). A typical example corresponds to $X_{k+1} = g(X_{0:k}, Y_{0:k})$ but we don't even need to assume that for the moment. Set $\mathcal{F}_k = \sigma(X_{0:k}, Y_{0:k})$ and assume that

$$\mathbb{P}(X_{k+1} \in A | \mathcal{F}_k) = P(X_k, A), \quad \mathbb{P} - \text{a.s.} \quad (1.1)$$

Since X_ℓ is \mathcal{F}_ℓ -measurable and $\mathcal{F}_\ell \subset \mathcal{F}_k$ for $\ell \leq k$, we deduce that $\sigma(X_{0:k}) \subset \mathcal{F}_k$. This allows to apply the tower property, which yields

$$\begin{aligned} \mathbb{P}(X_{k+1} \in A | X_{0:k}) &= \mathbb{E}[\mathbb{P}(X_{k+1} \in A | \mathcal{F}_k) | X_{0:k}] \\ &= \mathbb{E}[P(X_k, A) | X_{0:k}] = P(X_k, A), \quad \mathbb{P} - \text{a.s.} \end{aligned}$$

and therefore if we assume (1.1), then as soon as $(X_k)_{k \geq 0}$ is $(\mathcal{F}_k)_{k \geq 0}$ -adapted, we can conclude that $\{X_k : k \in \mathbb{N}\}$ is a Markov chain with Markov kernel P . Why is it useful? Well, sometimes you define iteratively X_{k+1} using other variables rather than $X_{0:k}$ only and therefore, considering $\mathbb{P}(X_{k+1} \in A | \mathcal{F}_k)$ is easier to deal with. Let us see it in action through a very simple example.

Example 1.3. Let $\{\epsilon_k : k \geq 1\}$ be iid random variables on \mathbb{R}^p with density f with respect to the Lebesgue measure on \mathbb{R}^p , and let $X_0 \sim \mu$. We assume that X_0 is independent of $\{\epsilon_k : k \in \mathbb{N}\}$. Define

$$X_{k+1} = aX_k + b\epsilon_{k+1}, \quad k \in \mathbb{N}.$$

Set $\mathcal{F}_0 = \sigma(X_0)$ and for $k \geq 1$, $\mathcal{F}_k = \sigma(X_0, \epsilon_{1:k})$. Since X_ℓ is a deterministic function of X_0 and $\epsilon_{1:\ell}$, we deduce that $(X_k)_{k \geq 0}$ is $(\mathcal{F}_k)_{k \geq 0}$ -adapted. Therefore we only need to check (1.1). Now, for any non-negative or bounded measurable function h on \mathbf{X} , we have

$$\mathbb{E}[h(X_{k+1})|\mathcal{F}_k] = \int_{-\infty}^{\infty} \underbrace{h(aX_k + b\epsilon)}_y f(\epsilon) d\epsilon = \int_{-\infty}^{\infty} \underbrace{h(y) f\left(\frac{y - aX_k}{b}\right)}_{P(X_k, dy)} \frac{1}{b^p} dy,$$

where the last equality follows from an adequate change of variable. Therefore $\{X_k : k \in \mathbb{N}\}$ is a Markov chain with Markov kernel

$$(x, A) \mapsto P(x, A) = \int_A f\left(\frac{y - ax}{b}\right) \frac{1}{b^p} dy.$$

In this example, we can check that \mathcal{F}_k is actually the natural filtration of $\{X_k : k \in \mathbb{N}\}$ but we even don't need to check this property for getting that $\{X_k : k \in \mathbb{N}\}$ is a Markov chain.

What have I learned so far? At this stage, I am able to solve typical exercises where some random variables are given and the question is to determine whether these random variables form a Markov chain or not and if yes, what is the expression of the associated Markov kernel.

As an illustration, interested readers might try to solve Exercise 7.1.

1.2.1 Additional notation

We are now ready (and eager) to absorb frantically other notation... For all $\mu \in \mathbf{M}_+(\mathbf{X})$, all Markov kernels P, Q on $\mathbf{X} \times \mathcal{X}$, and all measurable non-negative or bounded functions h on \mathbf{X} , we use the following convention and notation

- μP is the (positive) measure: $\mathcal{X} \ni A \mapsto \mu P(A) = \int \mu(dx) P(x, A)$,
- PQ is the Markov kernel: $(x, A) \mapsto \int_{\mathbf{X}} P(x, dy) Q(y, A)$,
- Ph is the measurable function $x \mapsto \int_{\mathbf{X}} P(x, dy) h(y)$.

It is easy to check that if μ is a probability measure, then μP is also a probability measure (since $\mu P(\mathbf{X}) = \int_{\mathbf{X}} \mu(dx) P(x, \mathbf{X}) = \int_{\mathbf{X}} \mu(dx) = 1$). With these notation, one can easily check from Fubini's theorem,

$$\begin{aligned} \mu(P(Qh)) &= (\mu P)(Qh) = (\mu(PQ))h \\ &= \mu((PQ)h) = \int \cdots \int_{\mathbf{X}^3} \mu(dx) P(x, dy) Q(y, dz) h(z). \end{aligned}$$

Therefore all these parenthesis can be discarded and we can write μPQh without any ambiguity. That's excellent news because it is simpler to deal with expressions without all these parenthesis. To sum up, measures act on the left side of a Markov kernel whereas functions acts on the right side. To make sure you have mastered all the notation, check your understanding with the following equalities $\delta_x P(A) = P(x, A) = P\mathbf{1}_A(x)$.

To finish up with notation, we now define the iterates of a Markov kernel P , which will come in very handy thereafter: for a given Markov kernel P on $\mathbf{X} \times \mathcal{X}$, define $P^0 = I$ where I is the identity kernel: $(x, A) \mapsto \mathbf{1}_A(x)$, and set for $k \geq 0$, $P^{k+1} = P^k P$.

Lemma 1.4. *Let $\{X_k : k \in \mathbb{N}\}$ be a Markov chain on the same probability space $(\Omega, \mathcal{G}, \mathbb{P})$ and taking values on X , with Markov kernel P and with initial distribution $\nu \in \mathcal{M}_1(\mathsf{X})$. Then, for any $n \in \mathbb{N}$, the law of $X_{0:n}$ is $\nu(dx_0) \prod_{i=0}^{n-1} P(x_i, dx_{i+1})$ (with the convention that $\prod_{i=0}^{-1} = 1$).*

Proof. Recall that for all $(n, A) \in \mathbb{N} \times \mathcal{X}$, $\mathbb{P}(X_{n+1} \in A | X_{0:n}) = P(X_n, A)$, \mathbb{P} -a.s. or equivalently for all non-negative measurable functions h_{k+1} on X , $\mathbb{E}[h_{n+1}(X_{n+1}) | X_{0:n}] = Ph_{n+1}(X_n)$ \mathbb{P} -a.s. We now show by induction that for all $n \in \mathbb{N}$,

$$(H_n) \text{ the law of } X_{0:n} \text{ is } \nu(dx_0) \prod_{i=0}^{n-1} P(x_i, dx_{i+1}).$$

We first note that (H_0) is true since by assumption, $X_0 \sim \nu$. Assume now that (H_n) holds for some $n \in \mathbb{N}$. Then, for all non-negative measurable functions h_0, \dots, h_{n+1} on X , the tower property yields

$$\mathbb{E} \left[\prod_{i=0}^{n+1} h_i(X_i) \right] = \mathbb{E} \left[\left(\prod_{i=0}^n h_i(X_i) \right) \mathbb{E}[h_{n+1}(X_{n+1}) | X_{0:n}] \right] = \mathbb{E} \left[\left(\prod_{i=0}^n h_i(X_i) \right) Ph_{n+1}(X_n) \right],$$

and since the inner term in the rhs only depends on $X_{0:n}$, we can apply (H_n) and thus,

$$\begin{aligned} \mathbb{E} \left[\prod_{i=0}^{n+1} h_i(X_i) \right] &= \int \cdots \int_{\mathsf{X}^{n+1}} \left[\nu(dx_0) \prod_{i=0}^{n-1} P(x_i, dx_{i+1}) \right] \left(\prod_{i=0}^n h_i(x_i) \right) Ph_{n+1}(x_n) \\ &= \int \cdots \int_{\mathsf{X}^{n+1}} \left[\nu(dx_0) \prod_{i=0}^n P(x_i, dx_{i+1}) \right] \left(\prod_{i=0}^{n+1} h_i(x_i) \right), \end{aligned}$$

showing that the law of $X_{0:n+1}$ is $\nu(dx_0) \prod_{i=0}^n P(x_i, dx_{i+1})$ and (H_{n+1}) is thus proved. \square

As a consequence, the marginal law of X_n is given by integrating $\nu(dx_0) \prod_{i=0}^{n-1} P(x_i, dx_{i+1})$ over $x_{0:n-1}$ and thus, for all $A \in \mathcal{X}$,

$$\mathbb{P}(X_n \in A) = \int \cdots \int_{\mathsf{X}^{n-1}} \mathbf{1}_A(X_n) \nu(dx_0) \prod_{i=0}^{n-1} P(x_i, dx_{i+1}) = \nu P^n(A),$$

that is, νP^n is the distribution of X_n or in a compact notation, $\boxed{X_n \sim \nu P^n}$.

1.3 Canonical space

So far, the situation is the following: the $\{X_k : k \in \mathbb{N}\}$ are already given and we check the two items in the definition of a Markov chain (Definition 1.2) with Markov kernel P and initial distribution ν . We now turn to the reverse situation where a couple (ν, P) of initial distribution and Markov kernel are given beforehand and we intend to construct the random variables $\{X_k : k \in \mathbb{N}\}$ on some convenient (common) probability space $(\Omega, \mathcal{F}, \mathbb{P})$ such that $\{X_k : k \in \mathbb{N}\}$ is a Markov chain with Markov kernel P and initial distribution ν .

1.3.1 A simpler problem

We start with an easier problem where we only want to construct $\{X_k : k \in [0 : n - 1]\}$ where n is some given positive integer. That is, we only consider a **finite range of integers** such that the first item in Definition 1.2 is satisfied. For a given $\nu \in \mathcal{M}_1(\mathsf{X})$, define the triplet $(\Omega_n, \mathcal{G}_n, \mathbb{P}_{\nu,n})$ as follows:

- $\Omega_n = \mathsf{X}^{n+1}$, $\mathcal{G}_n = \mathcal{X}^{\otimes(n+1)}$ and $\mathbb{P}_{\nu,n}$ is the probability measure defined on $(\Omega_n, \mathcal{G}_n)$ by

$$\mathcal{G}_n \ni A \mapsto \mathbb{P}_{\nu,n}(A) = \int \cdots \int_{\mathsf{X}^{n+1}} \mathbf{1}_A(\omega_{0:n}) \nu(d\omega_0) \prod_{i=1}^n P(\omega_{i-1}, d\omega_i),$$

and for $\omega \in \Omega_n$, set $X_k(\omega) = \omega_k$, (that $X_k(\omega)$ is the projection of the k -th component of ω).

We aim to show that for all $A \in \mathcal{X}$ and all $k \in [0 : n - 1]$, we have $\mathbb{P}_{\nu,n}(X_{k+1} \in A | X_{0:k-1}) = P(X_k, A)$, $\mathbb{P}_{\nu,n}$ -a.s. To do so, write for any $k \in [0 : n - 1]$, any non-negative measurable function h on X^{k+1} and any $A \in \mathcal{X}$

$$\begin{aligned} \mathbb{E}_{\nu,n} [h(X_{0:k}) \mathbf{1}_A(X_{k+1})] &= \int \cdots \int_{\mathsf{X}^{k+2}} h(\omega_{0:k}) \mathbf{1}_A(\omega_{k+1}) \nu(d\omega_0) \prod_{i=1}^{k+1} P(\omega_{i-1}, d\omega_i) \\ &= \int \cdots \int_{\mathsf{X}^{k+2}} h(\omega_{0:k}) P(\omega_k, A) \nu(d\omega_0) \prod_{i=1}^k P(\omega_{i-1}, d\omega_i) \\ &= \mathbb{E}_{\nu,n} [h(X_{0:k}) P(X_k, A)]. \end{aligned}$$

Since h is arbitrary, this is equivalent to saying that $\mathbb{P}_{\nu,n}(X_{k+1} \in A | X_{0:k}) = P(X_k, A)$, \mathbb{P} -a.s.

1.3.2 The general case

We now consider the general case where $k \in \mathbb{N}$ instead of $k \in [0 : n - 1]$. Define the coordinate process (X_n) by $X_n(\omega) = \omega_n$ for all $\omega \in \mathsf{X}^{\mathbb{N}}$. We will sometimes use $X_{k:\ell} : \omega \mapsto (\omega_k, \dots, \omega_\ell)$ for $k \leq \ell$ and by extension $X_{k:\infty} : \omega \mapsto (\omega_k, \dots, \omega_\ell, \omega_{\ell+1}, \dots)$. In particular, $X_{0:\infty}(\omega) = I(\omega) = \omega$ where I is the identity function.

Theorem 1.5. (The canonical space) *Let $(\mathsf{X}, \mathcal{X})$ be a measurable space and let P be a Markov kernel on $\mathsf{X} \times \mathcal{X}$. For every probability measure $\nu \in \mathcal{M}_1(\mathsf{X})$, there exists a unique probability measure \mathbb{P}_ν on the canonical space $(\mathsf{X}^{\mathbb{N}}, \mathcal{X}^{\otimes \mathbb{N}})$ such that, under \mathbb{P}_ν , the coordinate process $\{X_n : n \in \mathbb{N}\}$ is a Markov chain with Markov kernel P and initial distribution ν .*

This result is often referred to as the *Ionescu-Tulcea theorem*. Its proof goes far beyond the scope of this course and we will admit it here. Some other, much simpler proofs exist and are based on the Kolmogorov extension theorem, but they hold at the price of additive assumptions on the space (in contrast, we only assume here that $(\mathsf{X}, \mathcal{X})$ is a measurable space, which is quite minimal). In the canonical representation, we therefore set $\Omega = \mathsf{X}^{\mathbb{N}}$, $\mathcal{G} = \mathcal{X}^{\otimes \mathbb{N}}$ and $\mathbb{P} = \mathbb{P}_\nu$. In the particular case where the initial distribution ν is a Dirac mass, we use the compact notation $\mathbb{P}_x = \mathbb{P}_{\delta_x}$. Thus, the theorem allows to define not only one probability measure but a family of probability measures $(\mathbb{P}_\nu)_{\nu \in \mathcal{M}_1(\mathsf{X})}$ on the space of trajectories.

What are the relations between the probability measures $(\mathbb{P}_\nu)_{\nu \in \mathcal{M}_1(\mathsf{X})}$? A consequence of this theorem is that for all $A \in \mathcal{X}^{\otimes(n+1)}$, $\mathbb{P}_\nu(X_{0:n} \in A) = \int_A \nu(d\omega_0) \prod_{i=1}^n P(\omega_{i-1}, d\omega_i)$. Replacing ν by δ_{x_0} and comparing the two obtained expressions, we get

$$\mathbb{P}_\nu(X_{0:n} \in A) = \int_{\mathsf{X}} \nu(dx_0) \mathbb{P}_{x_0}(X_{0:n} \in A).$$

We can actually extend this result to any $A \in \mathcal{X}^{\otimes \mathbb{N}}$ by replacing the $n+1$ -tuple $X_{0:n}$ by the (infinite) trajectory $X_{0:\infty}$. First note the following equalities: $A = \{\omega \in A\} = \{\omega \in \Omega : X_{0:\infty}(\omega) \in A\} = \{X_{0:\infty} \in A\}$.

We then obtain the following identity: for all $A \in \mathcal{X}^{\otimes \mathbb{N}}$,

$$\mathbb{P}_\nu(A) = \mathbb{P}_\nu(X_{0:\infty} \in A) = \int_{\mathcal{X}} \nu(dx_0) \mathbb{P}_{x_0}(X_{0:\infty} \in A) = \int_{\mathcal{X}} \nu(dx_0) \mathbb{P}_{x_0}(A). \quad (1.2)$$

An illustration is given in Exercise 7.2.

1.3.3 The Markov property.

Define the shift operator S by $S : \mathcal{X}^{\mathbb{N}} \ni \omega \mapsto \omega' \in \mathcal{X}^{\mathbb{N}}$ where $\omega = (\omega_i)_{i \in \mathbb{N}}$ and $\omega' = (\omega_{i+1})_{i \in \mathbb{N}}$

Theorem 1.6. (The Markov property) For any $\nu \in \mathcal{M}_1(\mathcal{X})$, any non-negative or bounded function h on $\mathcal{X}^{\mathbb{N}}$ and any $n \in \mathbb{N}$,

$$\mathbb{E}_\nu [h \circ S^k | \mathcal{F}_k] = \mathbb{E}_{X_k}[h], \quad \mathbb{P}_\nu - a.s. \quad (1.3)$$

where $\mathcal{F}_k = \sigma(X_{0:k})$.

The expression of the Markov property, as it stands, may seem a bit cryptic. Recalling the definition of $X_{k:\infty}$, we have $\mathbb{P}_\nu - a.s.$,

$$\begin{aligned} \mathbb{E}_\nu [h(X_{k:\infty}) | \mathcal{F}_k] &= \mathbb{E}_\nu [h \circ S^k \circ X_{0:\infty} | \mathcal{F}_k] = \mathbb{E}_\nu [h \circ S^k \circ I | \mathcal{F}_k] \\ &= \mathbb{E}_\nu [h \circ S^k | \mathcal{F}_k] = \mathbb{E}_{X_k}[h] = \mathbb{E}_{X_k}[h \circ I] \\ &= \mathbb{E}_{X_k}[h(X_{0:\infty})]. \end{aligned}$$

Therefore, for any $\nu \in \mathcal{M}_1(\mathcal{X})$,

$$\mathbb{E}_\nu [h(X_{k:\infty}) | \mathcal{F}_k] = \mathbb{E}_{X_k}[h(X_{0:\infty})], \quad \mathbb{P}_\nu - a.s.$$

is another **equivalent expression of the Markov property**. This expression may seem easier to deal with but the reader has to be at ease with both formulations. A stronger version of the Markov property exists and is called (as expected) the strong Markov property: its statement is (1.3) with the exception that k is replaced by a stopping time τ and that the identity only holds on the event $\{\tau < \infty\}$. The strong Markov property is extremely important in Markov Chain theory but, quite surprisingly, it is not needed in this basic course. To satisfy readers' curiosity, Exercise 7.3 states and proves the Strong Markov property.

1.4 After studying this chapter...

- a) I can write perfectly expression of Markov kernels if it is asked.
- b) I understand the different notation $\mu PQf...$
- c) I perfectly understand the canonical space.
- d) I can understand (1.2).
- e) I perfectly understand the Markov property (1.3).
- f) I love Markov chains.

Highlights

1.A Andrey Markov (source: wikipedia).



Andrey Andreyevich Markov (1856–1922) was a Russian mathematician best known for his work on stochastic processes. A primary subject of his research later became known as Markov chains and Markov processes.

Markov and his younger brother Vladimir Andreevich Markov (1871–1897) proved the Markov brothers' inequality. His son, another Andrei Andreyevich Markov (1903–1979), was also a notable mathematician, making contributions to constructive mathematics and recursive function theory.

Andrey Markov was born on 14 June 1856 in Russia. He attended Petersburg Grammar, where he was seen as a rebellious student by a select few teachers. In his academics he performed poorly in most subjects other than mathematics. Later in life he attended Petersburg University; among his teachers were Yulian Sokhotski (differential calculus, higher algebra), Konstantin Posse (analytic geometry), Yegor Zolotarev (integral calculus), Pafnuty Chebyshev (number theory and probability theory), Aleksandr Korkin (ordinary and partial differential equations), Mikhail Okatov (mechanism theory), Osip Somov (mechanics), and Nikolai Budaev (descriptive and higher geometry). He completed his studies at the University and was later asked if he would like to stay and have a career as a Mathematician. He later taught at high schools and continued his own mathematical studies. In this time he found a practical use for his mathematical skills. He figured out that he could use chains to model the alliteration of vowels and consonants in Russian literature. He also contributed to many other mathematical aspects in his time. He died at age 66 on 20 July 1922.

Chapter 2

Invariant probability measures

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Keywords: Invariant probability measures, existence, uniqueness, reversibility.

2.1 Invariant probability measures: existence

Definition 2.1. We say that $\pi \in M_1(X)$ is an invariant probability measure for the Markov kernel P on $X \times \mathcal{X}$ if $\pi P = \pi$.

In words, if (X_k) is a Markov chain with Markov kernel P and assuming that $X_0 \sim \pi$, then for all $k \geq 1$, we have $X_k \sim \pi$. (This is due to the fact that applying P^k on both sides of $\pi P = \pi$ shows that $\pi P^{k+1} = \pi P^k$ and therefore, for all $k \in \mathbb{N}$, $\pi P^k = \pi$). This result on the (marginal) distribution of X_k may be extended to n -tuples.

More precisely, it can be readily checked that if π is an *invariant probability measure* for P , then the sequence of random variables $\{X_k : k \in \mathbb{N}\}$ is a *strongly stationary sequence* under \mathbb{P}_π (in the sense that for all $n, p \in \mathbb{N}^*$, and all n -tuple $k_{1:n}$, the random vector $(X_{k_1}, \dots, X_{k_n})$ follows the same distribution as $(X_{k_1+p}, \dots, X_{k_n+p})$).

Exercises 7.4 and 7.5 illustrate the existence of stationary distributions for Markov chains. We now introduce the notion of reversibility for a Markov kernel. This will be of crucial importance for designing Markov kernels with a given invariant probability measure.

Definition 2.2. Let $\pi \in M_1(X)$ and P be a Markov kernel on $X \times \mathcal{X}$. We say that P is π -reversible if and only if (with infinitesimal notation)

$$\pi(dx)P(x, dy) = \pi(dy)P(y, dx), \tag{2.1}$$

that is, for all measurable bounded or non-negative functions h on $(\mathsf{X}^2, \mathcal{X}^{\otimes 2})$,

$$\iint_{\mathsf{X}^2} h(x, y) \pi(dx) P(x, dy) = \iint_{\mathsf{X}^2} h(x, y) \pi(dy) P(y, dx). \quad (2.2)$$

In words, a Markov kernel P is π -reversible if and only if the probability measure $\pi(dx)P(x, dy)$ is symmetric with respect to (x, y) .

Proposition 2.3. *Let P be a Markov kernel on $\mathsf{X} \times \mathcal{X}$. Let $\pi \in \mathsf{M}_1(\mathsf{X})$ such that P is π -reversible, then the Markov kernel P is π -invariant.*

Proof. For any $A \in \mathcal{X}$, we have by the reversibility relation

$$\pi P(A) = \iint_{\mathsf{X}^2} \mathbf{1}_A(y) \pi(dx) P(x, dy) = \iint_{\mathsf{X}^2} \mathbf{1}_A(y) \pi(dy) P(y, dx) = \int_A \pi(dy) \underbrace{P(y, \mathsf{X})}_1 = \pi(A),$$

which finishes the proof. \square

What are the consequences? If you want to check easily that a kernel P is π -invariant, it is sufficient to check that it is π -reversible.

Exercise 7.6 gives an example of π -reversible kernel.

2.1.1 Metropolis-Hastings (MH) algorithms

In this section, we are given a probability measure $\pi \in \mathsf{M}_1(\mathsf{X})$ and the idea now is to construct a Markov chain $\{X_k : k \in \mathbb{N}\}$ admitting π as invariant probability measure, in which case we say that π is a target distribution. In other words, we try to find a Markov kernel P on $\mathsf{X} \times \mathcal{X}$ such that P is π -invariant. The reason for that is that an invariant probability measure will be a good candidate for the “limiting” distribution of $\{X_k : k \in \mathbb{N}\}$ (in some sense to be defined) and this in turn, will allow us to provide an approximation $\pi(h)$:

$$\pi(h) = \int_{\mathsf{X}} h(x) \pi(dx) \approx n^{-1} \sum_{k=0}^{n-1} h(X_k).$$

2.1.1.1 Construction of the kernel

For simplicity we now assume that π has a density with respect to some dominating σ -finite measure λ and by abuse of notation, we also denote by π this density, that is we write $\pi(dx) = \pi(x)\lambda(dx)$ and we assume that this density π is **positive**.

Moreover, let Q be Markov kernel on $\mathsf{X} \times \mathcal{X}$ such that $Q(x, dy) = q(x, y)\lambda(dy)$, that is, for any $x \in \mathsf{X}$, $Q(x, \cdot)$ is also dominated by λ and denoting by $q(x, \cdot)$ this density, we assume for simplicity that $q(x, y)$ is **positive** for all $x, y \in \mathsf{X}$. At this stage, there is almost no link between Q and the target distribution π .

For a given function $\alpha : \mathsf{X}^2 \rightarrow [0, 1]$, consider the following Algorithm 1.

In words, Q allows to propose a candidate for the next value of the Markov chain (X_k) and this candidate will be accepted or refused according to a probability that depends on the function α .

input : n
output: X_0, \dots, X_n
 At $t = 0$, draw X_0 according to some arbitrary distribution
for $t \leftarrow 0$ **to** $n - 1$ **do**
 • Draw independently $Y_{t+1} \sim Q(X_t, \cdot)$ and $U_{t+1} \sim \text{Unif}(0, 1)$
 • Set $X_{t+1} = \begin{cases} Y_{t+1} & \text{if } U_{t+1} \leq \alpha(X_t, Y_{t+1}) \\ X_t & \text{otherwise} \end{cases}$
end

Algorithm 1: The Metropolis Algorithm

We will now choose conveniently α in such a way that (X_k) is a Markov chain with invariant probability measure π . The concept of π -reversibility will help us. To do so, let us assume that for all $x, y \in \mathsf{X}$,

$$\pi(x)\alpha(x, y)q(x, y) = \pi(y)\alpha(y, x)q(y, x), \quad (2.3)$$

and let us show that it implies that the Markov kernel P associated to (X_k) is π -reversible.

First, we write down the Markov kernel associated to (X_k) : in passing, this is an excellent opportunity to check if we are able to express explicitly a Markov kernel by analyzing conveniently the update transition. Denote $\mathcal{F}_t = \sigma(X_0, U_{1:t}, Y_{1:t})$ and note that (X_t) is adapted to the filtration (\mathcal{F}_t) (which is equivalent to $\sigma(X_{0:t}) \subset \mathcal{F}_t$). Then, setting $\bar{\alpha}(x) = 1 - \int_{\mathsf{X}} Q(x, dy)\alpha(x, y)$, we have for any bounded or non-negative measurable function h on X and any $t \in \mathbb{N}$,

$$\begin{aligned} \mathbb{E}[h(X_{t+1})|\mathcal{F}_t] &= \mathbb{E}[\mathbf{1}_{\{U_{t+1} < \alpha(X_t, Y_{t+1})\}}h(Y_{t+1})|\mathcal{F}_t] + \mathbb{E}[\mathbf{1}_{\{U_{t+1} \geq \alpha(X_t, Y_{t+1})\}}h(X_t)|\mathcal{F}_t] \\ &= \int_{\mathsf{X}} Q(X_t, dy)\alpha(X_t, y)h(y) + \bar{\alpha}(X_t)h(X_t) \\ &= \int_{\mathsf{X}} \underbrace{Q(X_t, dy)\alpha(X_t, y) + \bar{\alpha}(X_t)\delta_{X_t}(dy)}_{P_{(\pi, Q)}^{MH}(X_t, dy)} h(y) = P_{(\pi, Q)}^{MH}h(X_t). \end{aligned}$$

Therefore, $\{X_t : t \in \mathbb{N}\}$ is a Markov chain with Markov kernel

$$P_{(\pi, Q)}^{MH}(x, dy) = Q(x, dy)\alpha(x, y) + \bar{\alpha}(x)\delta_x(dy). \quad (2.4)$$

Lemma 2.4. *The Markov kernel $P_{(\pi, Q)}^{MH}$ is π -reversible if and only if*

$$\pi(dx)Q(x, dy)\alpha(x, y) = \pi(dy)Q(y, dx)\alpha(y, x). \quad (2.5)$$

In this literature, (2.5) is often called the **detailed balance condition**.

Proof. First, note that

$$\pi(dx)\bar{\alpha}(x)\delta_x(dy) = \pi(dy)\bar{\alpha}(y)\delta_y(dx). \quad (2.6)$$

Indeed, for any measurable function h on X^2 , we have

$$\begin{aligned} \iint_{\mathsf{X}^2} h(x, y)\pi(dx)\bar{\alpha}(x)\delta_x(dy) &= \int_{\mathsf{X}} h(x, x)\pi(dx)\bar{\alpha}(x) \\ &= \int_{\mathsf{X}} h(y, y)\pi(dy)\bar{\alpha}(y) = \iint_{\mathsf{X}^2} h(x, y)\pi(dy)\bar{\alpha}(y)\delta_y(dx). \end{aligned}$$

Combining (2.4) with (2.6), we obtain that $P_{\langle \pi, Q \rangle}^{MH}$ is π -reversible if and only if the detailed balance condition (2.5) is satisfied. This completes the proof. \square

2.1.1.2 Acceptance probability

We now make use of Lemma 2.4 in order to find an explicit expression of the acceptance probability α . We have the following lemma.

Lemma 2.5. Denote $\alpha^{MH}(x, y) = \min\left(\frac{\pi(y)q(y, x)}{\pi(x)q(x, y)}, 1\right)$ and $\alpha^b(x, y) = \frac{\pi(y)q(y, x)}{\pi(x)q(x, y) + \pi(y)q(y, x)}$. Then, any $\alpha \in \{\alpha^{MH}, \alpha^b\}$ satisfies the detailed balance condition (2.5). Moreover, any other $\alpha \in [0, 1]$ that satisfies the detailed balance condition is dominated by α^{MH} in the sense that: for $\lambda^{\otimes 2}$ -almost all $x, y \in X$,

$$\alpha(x, y) \leq \alpha^{MH}(x, y). \quad (2.7)$$

Proof. The fact that any $\alpha \in \{\alpha^{MH}, \alpha^b\}$ satisfies $\pi(x)q(x, y)\alpha(x, y) = \pi(y)q(y, x)\alpha(y, x)$ for $\lambda^{\otimes 2}$ -almost all $x, y \in X$, is immediate, by replacing α by its expression. It remains to check (2.7). Assume now that for $\lambda^{\otimes 2}$ -almost all $x, y \in X$,

$$\pi(x)q(x, y)\alpha(x, y) = \pi(y)q(y, x)\alpha(y, x).$$

then, using that $\alpha(y, x) \leq 1$ shows that $\alpha(x, y) \leq \frac{\pi(y)q(y, x)}{\pi(x)q(x, y)}$. Moreover, $\alpha(x, y) \leq 1$ and this finally implies

$$\alpha(x, y) \leq \min\left(\frac{\pi(y)q(y, x)}{\pi(x)q(x, y)}, 1\right) = \alpha^{MH}(x, y),$$

which completes the proof. \square

According to (2.7), α^{MH} is actually the highest acceptance probability among the acceptance probabilities such that $P_{\langle \pi, Q \rangle}^{MH}$ is π -reversible and therefore, this acceptance is widely used in practice (in the sense that we expect that a Markov kernel that accepts often, explores the space more rapidly and therefore is preferable to another one with less acceptance probability). In what follows, unless otherwise stated, **we implicitly assume that the Markov kernel $P_{\langle \pi, Q \rangle}^{MH}$ is associated to the acceptance probability α^{MH} .**

Exercise 7.7 shows other examples of possible acceptance probabilities.

Example 2.6. (The independence sampler) If the proposition kernel is $Q(x, dy) = q(y)\lambda(dy)$ where q is a density wrt λ on X , then at each time step, the proposed candidate is drawn irrespective of the current value of the Markov chain (this is because, $Q(x, dy)$ does not depend on x), that is, in the step 2(a) of Algorithm 1, we draw $Y_{t+1} \sim q(\cdot)$. In such case, the acceptance probability is $\alpha(x, y) = \min\left(\frac{\pi(y)q(x)}{\pi(x)q(y)}, 1\right)$ and the Metropolis-Hastings algorithm is called the *Independence Sampler*.

Another important example is the following.

Example 2.7. (The random walk MH sampler) If $X = \mathbb{R}^p$ and if the proposition kernel is $Q(x, dy) = q(y - x)\lambda(dy)$ where q is a symmetric density wrt λ on X , (by symmetric, we mean that $q(u) = q(-u)$ for all $u \in X$) then at each time step in Algorithm 1, we draw a candidate $Y_{t+1} \sim q(y - X_k)\lambda(dy)$. In such case, the acceptance probability is $\alpha(x, y) = \min\left(\frac{\pi(y)}{\pi(x)}, 1\right)$ and the associated algorithm is called the (*symmetric*) *Random Walk Metropolis-Hasting*. Another way of writing the proposition update is $Y_{t+1} = X_k + \eta_k$ where $\eta_k \sim q(\cdot)$.

2.2 Invariant probability measure: uniqueness

We start with a very simple lemma that will be useful for finding sufficient conditions for uniqueness.

Lemma 2.8. *If P admits two distinct invariant probability measures, it also admits distinct invariant probability measures π_0 and π_1 that are mutually singular, i.e., such that there exists $A \in \mathcal{X}$ such that $\pi_0(A) = \pi_1(A^c) = 0$.*

Proof. Let ζ_0, ζ_1 be two distinct invariant probability measures for P . Both have densities with respect to some common dominating measure (for example, taking $\zeta = \zeta_1 + \zeta_2$, we have that ζ dominates both ζ_0 and ζ_1 , which can be seen from the implication $\zeta(A) = 0 \Rightarrow (\zeta_1(A) = 0 \text{ and } \zeta_2(A) = 0)$ for any $A \in \mathcal{X}$ and according to the Radon-Nikodym theorem, if a measure dominates another one, the latter has a density with respect to the former). Write then $\zeta_0(dx) = f_0(x)\zeta(dx)$ and $\zeta_1(dx) = f_1(x)\zeta(dx)$ where f_0, f_1 are non-negative measurable functions on \mathbf{X} . Define the positive part $(\zeta_1 - \zeta_0)^+$ and the negative part $(\zeta_1 - \zeta_0)^-$ of the signed measure $\zeta_1 - \zeta_0$ by $(\zeta_1 - \zeta_0)^+(dx) = [f_1(x) - f_0(x)]^+\zeta(dx)$ and $(\zeta_1 - \zeta_0)^-(dx) = [f_1(x) - f_0(x)]^-\zeta(dx)$. Then,

$$\begin{aligned} (\zeta_1 - \zeta_0)^+ P \mathbf{1}_A &= \int_{\mathbf{X}} \zeta(dx) [f_1(x) - f_0(x)]^+ P(x, A) \\ &\geq \int_{\mathbf{X}} \zeta(dx) [f_1(x) - f_0(x)] P(x, A) \\ &\geq \zeta_1 P(A) - \zeta_0 P(A) = \zeta_1(A) - \zeta_0(A). \end{aligned}$$

Therefore, $(\zeta_1 - \zeta_0)^+ P$ is a (non-negative) measure that is greater than the signed measure $\zeta_1 - \zeta_0$. Since the positive part $(\zeta_1 - \zeta_0)^+$ is also the smallest (non-negative) measure that is greater than $\zeta_1 - \zeta_0$, we conclude that $(\zeta_1 - \zeta_0)^+ \leq (\zeta_1 - \zeta_0)^+ P$. The measure $(\zeta_1 - \zeta_0)^+ P - (\zeta_1 - \zeta_0)^+$ is therefore non-negative and we have

$$[(\zeta_1 - \zeta_0)^+ P - (\zeta_1 - \zeta_0)^+](\mathbf{X}) = \int_{\mathbf{X}} (\zeta_1 - \zeta_0)^+(dx) \underbrace{P(x, \mathbf{X})}_1 - (\zeta_1 - \zeta_0)^+(\mathbf{X}) = 0.$$

Finally, $(\zeta_1 - \zeta_0)^+ = (\zeta_1 - \zeta_0)^+ P$. The probability measure $\pi_0 = \frac{(\zeta_1 - \zeta_0)^+}{(\zeta_1 - \zeta_0)^+(\mathbf{X})}$ is thus an invariant probability measure for P . Replacing $(\zeta_1 - \zeta_0)^+$ by $(\zeta_1 - \zeta_0)^-$, we obtain in the same way that $\pi_1 = \frac{(\zeta_1 - \zeta_0)^-}{(\zeta_1 - \zeta_0)^-(\mathbf{X})}$ is an invariant probability measure. We can easily check that taking $A = \{f_0 \geq f_1\}$, we have $\pi_0(A) = \pi_1(A^c) = 0$, showing that these probability measures are mutually singular. \square

To be rigorous, in the course of the proof, we actually need some results on the positive and negative part of a signed-measure. The interested reader may work on the following exercise to fully understand the previous proof:

Exercise 2.9. Define $M_s(\mathbf{X})$ the set of signed-measures. Let $\mu \in M_s(\mathbf{X})$ and assume that $\mu \preceq \zeta$ where $\zeta \in M_+(\mathbf{X})$ (in the sense that we have the implication: if for some $A \in \mathcal{X}$, $\zeta(A) = 0$, then $\mu(A) = 0$). According to the Radon-Nikodym theorem, there exists a measurable function h such that $\mu(dx) = h(x)\zeta(dx)$. Define $\mu^+(dx) = |h(x)|\zeta(dx)$.

1. Show that the measure μ^+ is well-defined (in the sense that the measure $|h(x)|\zeta(dx)$ does not depend on the measure ζ , provided that the ζ dominates μ .)
2. Show that for ζ -almost all $x \in \mathbf{X}$, $|h(x)| \leq 1$.
3. Assume that there exists $\nu \in M_+(\mathbf{X})$ such that for all $A \in \mathcal{X}$, we have $\mu(A) \leq \nu(A)$. Show that $\mu^+(A) \leq \nu(A)$ for all $A \in \mathcal{X}$.

We now make use of Lemma 2.8 in order to give a sufficient condition for uniqueness.

Proposition 2.10. *Assume that there exists a non-null measure $\mu \in M_+(\mathbf{X})$ satisfying the following property:*

- *For all $A \in \mathcal{X}$ such that $\mu(A) > 0$ and for all $x \in \mathbf{X}$, there exists $n \in \mathbb{N}$ such that $P^n(x, A) > 0$.*

Then, P admits at most one invariant probability measure.

If the assumption of Proposition 2.10 holds, we say that P is μ -**irreducible** and in such case, μ is called an **irreducibility measure** for P .

Proof. The proof is by contradiction. Assume that there exists two distinct invariant probability measures. According to Lemma 2.8, we can consider two invariant probability measures π_1 and π_2 that are mutually singular. Under the assumptions of the Proposition, let $A \in \mathcal{X}$ such that $\mu(A) > 0$. Then, for any $i \in \{1, 2\}$, we have

$$0 < \int_{\mathbf{X}} \pi_i(dx) \underbrace{\sum_{n=0}^{\infty} P^n(x, A)}_{>0} = \sum_{n=0}^{\infty} \pi_i P^n(A) = \sum_{n=0}^{\infty} \pi_i(A),$$

which in turn implies that $\pi_i(A) > 0$. The contraposed implication gives that if for some $i \in \{1, 2\}$, $\pi_i(A) = 0$, then $\mu(A) = 0$. Now, since $\{\pi_i : i \in \{1, 2\}\}$ are mutually singular, there exists $A \in \mathcal{X}$ such that $\pi_1(A) = \pi_2(A^c) = 0$ and this shows that $\mu(A) = \mu(A^c) = 0$ which is impossible. \square

Exercise 7.9 gives an example where Proposition 2.10 applies.

2.2.1 Application to Metropolis-Hastings algorithms.

We have already seen that $P_{(\pi, Q)}^{MH}$ is π -invariant and we have assumed that $Q(x, dy) = q(x, y)\lambda(dy)$ and $\pi(dy) = \pi(y)\lambda(dy)$ and for simplicity, we said that for all $x, y \in \mathbf{X}$, $q(x, y) > 0$ and $\pi(y) > 0$. This in turn implies that $\alpha(x, y) = \alpha^{MH}(x, y) > 0$ and therefore if $\lambda(A) > 0$, then for all $x \in \mathbf{X}$,

$$P(x, A) \geq \int_A \underbrace{q(x, y)\alpha(x, y)}_{>0} \lambda(dy) > 0.$$

This shows that P is λ -irreducible and therefore π is the **unique invariant probability measure for P** .

2.3 After studying this chapter...

- I can understand the link between reversibility and invariant measure.
- If asked, I can check that MH chains are reversible.
- I understand the form of the acceptance probability.
- Independence sampling and random walk MH have no secrets for me and I am able to implement them.
- If asked, I can show that an invariant measure is unique by using Proposition 2.10
- I find that Metropolis-Hasting algorithms are magical.

Highlights

2.A Monte Carlo methods. Source: Wikipedia

The term "Monte Carlo method" was coined in the 1940s by physicists working on nuclear weapon projects in the Los Alamos National Laboratory.

Enrico Fermi in the 1930s and Stanislaw Ulam in 1946 first had the idea. Ulam later contacted John Von Neumann to work on it.

Physicists at Los Alamos Scientific Laboratory were investigating radiation shielding and the distance that neutrons would likely travel through various materials. Despite having most of the necessary data, such as the average distance a neutron would travel in a substance before it collided with an atomic nucleus or how much energy the neutron was likely to give off following a collision, the problem could not be solved with analytical calculations. John von Neumann and Stanislaw Ulam suggested that the problem be solved by modeling the experiment on a computer using chance. Being secret, their work required a code name. Von Neumann chose the name "Monte Carlo". The name is a reference to the Monte Carlo Casino in Monaco where Ulam's uncle would borrow money to gamble.

Random methods of computation and experimentation (generally considered forms of stochastic simulation) can be arguably traced back to the earliest pioneers of probability theory (see, e.g., Buffon's needle, and the work on small samples by William Sealy Gosset), but are more specifically traced to the pre-electronic computing era. The general difference usually described about a Monte Carlo form of simulation is that it systematically "inverts" the typical mode of simulation, treating deterministic problems by first finding a probabilistic analog (see Simulated annealing). Previous methods of simulation and statistical sampling generally did the opposite: using simulation to test a previously understood deterministic problem. Though examples of an "inverted" approach do exist historically, they were not considered a general method until the popularity of the Monte Carlo method spread.

Monte Carlo methods were central to the simulations required for the Manhattan Project, though were severely limited by the computational tools at the time. Therefore, it was only after electronic computers were first built (from 1945 on) that Monte Carlo methods began to be studied in depth. In the 1950s they were used at Los Alamos for early work relating to the development of the hydrogen bomb, and became popularized in the fields of physics, physical chemistry, and operations research. The Rand Corporation and the U.S. Air Force were two of the major organizations responsible for funding and disseminating information on Monte Carlo methods during this time, and they began to find a wide application in many different fields.

Uses of Monte Carlo methods require large amounts of random numbers, and it was their use that spurred the development of pseudorandom number generators, which were far quicker to use than the tables of random numbers which had been previously used for statistical sampling.

Chapter 3

Ergodicity and Law of Large numbers

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Keywords: Ergodicity, Birkhoff ergodic theorem.

We now focus on properties of Markov chains with unique invariant probability measures. We will show in this part that such Markov chains turn out to be ergodic in some sense to be defined (actually in this type of ergodicity is linked with ergodic dynamical systems) and this, in turn, allows to apply the Birkhoff ergodic theorem so that a law of large number will hold.

Let us start with a refresher on ergodic results.

3.1 Dynamical systems.

Definition 3.1. (Dynamical system) A dynamical system \mathcal{D} is a quadruplet $\mathcal{D} = (\Omega, \mathcal{F}, \mathbb{P}, T)$ where $(\Omega, \mathcal{F}, \mathbb{P})$ is a probability space and $T : \Omega \rightarrow \Omega$ is a measurable mapping such that $\mathbb{P} = \mathbb{P} \circ T^{-1}$.

Lemma 3.2. The collection of sets $\mathcal{I} = \{A \in \mathcal{F} : \mathbf{1}_A = \mathbf{1}_A \circ T\}$ is a σ -field and any set in \mathcal{I} is called an invariant set.

Proof. Indeed, obviously $\Omega \in \mathcal{I}$. Moreover, if $A \in \mathcal{I}$, then for all $\omega \in \Omega$,

$$\mathbf{1}_{A^c}(\omega) = 1 - \mathbf{1}_A(\omega) = 1 - \mathbf{1}_A \circ T(\omega) = \mathbf{1}_{A^c} \circ T(\omega),$$

showing that $A^c \in \mathcal{I}$. Now, consider a countable family of $A_i \in \mathcal{I}$ where $i \in \mathbb{N}$. Then $\omega \in \bigcap_{i \in \mathbb{N}} A_i$ if and only if for all $i \in \mathbb{N}$, $\omega \in A_i$ which is in turn equivalent to $T(\omega) \in A_i$. All in all we have shown that $\omega \in \bigcap_{i \in \mathbb{N}} A_i$ if and only if $T(\omega) \in \bigcap_{i \in \mathbb{N}} A_i$. This shows that \mathcal{I} is a σ -field. \square

Definition 3.3. (Ergodicity) A dynamical system $(\Omega, \mathcal{F}, \mathbb{P}, T)$ is said to be *ergodic* if \mathcal{I} is trivial, that is, $A \in \mathcal{I}$ implies that either $\mathbb{P}(A) = 0$ or $\mathbb{P}(A) = 1$.

What interests us in the first place is that ergodic dynamical system satisfies the Birkhoff ergodic theorem, as detailed below. We first define the iterates of T by $T^0 = I$, and for all $k \geq 1$, $T^k = T^{k-1} \circ T$.

Theorem 3.4. (The Birkhoff theorem) *Let $\mathcal{D} = (\Omega, \mathcal{F}, \mathbb{P}, T)$ be an ergodic dynamical system and let $h \in \mathcal{L}_1(\Omega)$. Then,*

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} h \circ T^k = \mathbb{E}[h], \quad \mathbb{P} - a.s.$$

Exercise 7.11 proves this theorem.

3.2 Markov chains and ergodicity

Let us now relate Markov chains to dynamical systems. Recall the shift operator $S : \mathcal{X}^{\mathbb{N}} \ni \omega \mapsto \omega' \in \mathcal{X}^{\mathbb{N}}$ where $\omega = (\omega_i)_{i \in \mathbb{N}}$ and $\omega' = (\omega_{i+1})_{i \in \mathbb{N}}$. It is important to note that in general $(\mathcal{X}^{\mathbb{N}}, \mathcal{X}^{\otimes \mathbb{N}}, \mathbb{P}_\nu, S)$ is not a dynamical system except if the initial distribution ν is actually invariant wrt P .

Lemma 3.5. *Let P be a Markov kernel admitting an invariant probability measure π . Then, the quadruplet $(\mathcal{X}^{\mathbb{N}}, \mathcal{X}^{\otimes \mathbb{N}}, \mathbb{P}_\pi, S)$ is a dynamical system.*

Proof. Indeed, the relation $\mathbb{P}_\pi = \mathbb{P}_\pi \circ S^{-1}$ is equivalent to the fact that for any $A \in \mathcal{X}^{\otimes \mathbb{N}}$, $\mathbb{P}_\pi(A) = \mathbb{P}_\pi(X_{0:\infty} \in A) = \mathbb{P}_\pi(X_{0:\infty} \in S^{-1}(A)) = \mathbb{P}_\pi(X_{1:\infty} \in A)$, which is a consequence of the fact that the sequence of random variables $\{X_k : k \in \mathbb{N}\}$ is strongly stationary under \mathbb{P}_π . \square

The relation $\mathbb{P}_\pi = \mathbb{P}_\pi \circ S^{-1}$ tells us that for any $A \in \mathcal{X}^{\otimes \mathbb{N}}$, we have

$$\mathbb{E}_\pi[\mathbf{1}_A] = \mathbb{P}_\pi(A) = \mathbb{P}_\pi \circ S^{-1}(A) = \mathbb{P}_\pi(S^{-1}(A)) = \mathbb{E}_\pi[\mathbf{1}_{S^{-1}(A)}] = \mathbb{E}_\pi[\mathbf{1}_A \circ S],$$

This, in turn, implies that for any $h \in \mathcal{F}_+(X)$,

$$\mathbb{E}_\pi[h] = \mathbb{E}_\pi[h \circ S].$$

We now provide conditions under which a Markov kernel induces an ergodic dynamical system $(\mathcal{X}^{\mathbb{N}}, \mathcal{X}^{\otimes \mathbb{N}}, \mathbb{P}_\pi, S)$. In what follows, $\mathcal{F}_k = \sigma(X_{0:k})$. Since invariant sets A belong to $\mathcal{X}^{\otimes \mathbb{N}}$, it can be (and it will be) useful to get approximations of A by sets in \mathcal{F}_k where k is conveniently chosen.

Lemma 3.6. (The approximation lemma) *Any set $A \in \mathcal{X}^{\otimes \mathbb{N}}$ satisfies the following approximation property:*

- for all $\delta > 0$, there exist $k \in \mathbb{N}$ and $B \in \mathcal{F}_k$ such that

$$\mathbb{E}_\pi[|\mathbf{1}_A - \mathbf{1}_B|] \leq \delta. \quad (3.1)$$

Proof. This is a typical use of the monotone class theorem. Consider the class \mathcal{M} of sets $A \in \mathcal{X}^{\otimes \mathbb{N}}$, for which the approximation (3.1) holds.

- If $A_0, A_1 \in \mathcal{M}$ and $A_0 \subset A_1$, then $A_1 \setminus A_0 \in \mathcal{M}$. This is actually immediate from the following identities, valid for all sets A_0, A_1, B_0, B_1 ,

$$\begin{aligned}\mathbf{1}_{A_1 \setminus A_0} - \mathbf{1}_{B_1 \setminus B_0} &= \mathbf{1}_{A_1} - \mathbf{1}_{A_1} \mathbf{1}_{A_0} - (\mathbf{1}_{B_1} - \mathbf{1}_{B_1} \mathbf{1}_{B_0}) \\ &= \mathbf{1}_{A_1} - \mathbf{1}_{B_1} - \mathbf{1}_{A_1} (\mathbf{1}_{A_0} - \mathbf{1}_{B_0}) + (\mathbf{1}_{B_1} - \mathbf{1}_{A_1}) \mathbf{1}_{B_0},\end{aligned}$$

which implies $\mathbb{E}[|\mathbf{1}_{A_1 \setminus A_0} - \mathbf{1}_{B_1 \setminus B_0}|] \leq 2\mathbb{E}[|\mathbf{1}_{A_1} - \mathbf{1}_{B_1}|] + \mathbb{E}[|\mathbf{1}_{A_0} - \mathbf{1}_{B_0}|]$

- If $A_n \uparrow A$ where $A_n \in \mathcal{M}$ and $A_n \subset A_{n+1}$ for all $n \geq 0$. Then, setting $A = \cup_n A_n \in \mathcal{M}$, we have

$$\lim_{n \rightarrow \infty} \mathbf{1}_{A_n} = \mathbf{1}_A,$$

and this immediately implies that $A \in \mathcal{M}$ (check it carefully).

Then, \mathcal{M} is a monotone class that contains all the $(\mathcal{F}_k)_{k \geq 0}$ and therefore, it contains $\sigma(\cup_{k=0}^{\infty} \mathcal{F}_k) = \mathcal{X}^{\otimes \mathbb{N}}$. This finishes the proof. \square

We now have all the tools to state and prove an extremely powerful result on Markov chains and ergodicity.

Theorem 3.7. *Let P be a Markov kernel on $X \times \mathcal{X}$. Assume that P admits a unique invariant probability measure π . Then, the dynamical system $(X^{\mathbb{N}}, \mathcal{X}^{\otimes \mathbb{N}}, \mathbb{P}_\pi, S)$ is ergodic.*

Proof. Let P be a Markov kernel that admits a unique invariant probability measure π and let $A \in \mathcal{I} = \{A \in \mathcal{X}^{\otimes \mathbb{N}} : \mathbf{1}_A = \mathbf{1}_A \circ S\}$.

Assume that $\mathbb{P}_\pi(A) > 0$. We will show that $\mathbb{P}_\pi(A) = 1$ and this will prove that the dynamical system $(X^{\mathbb{N}}, \mathcal{X}^{\otimes \mathbb{N}}, \mathbb{P}_\pi, S)$ is ergodic.

Before diving into the proof, let us take a few minutes to analyse the situation... The quantity of interest is $\mathbb{P}_\pi(A)$ while the assumption is on π (it is the unique invariant probability measure for P). A first step is to relate $\mathbb{P}_\pi(A)$ with π ... That reminds us (1.2), which allows to write

$$\mathbb{P}_\pi(A) = \int_{\mathbf{X}} \pi(dx) \mathbb{E}_x[\mathbf{1}_A] = \pi(h_A), \quad \text{where we have set } h_A(x) = \mathbb{E}_x[\mathbf{1}_A].$$

The proof proceeds in two steps. We first establish some results on h_A and then, deduce properties on $\mathbb{P}_\pi(A)$ by constructing, from π and A , another invariant probability measure π_A .

- (i) $(h_A(X_n) \text{ does not depend on } n, \mathbb{P}_\pi - a.s.)$. To see this, first write for any $n \in \mathbb{N}$,

$$\begin{aligned}\mathbb{E}_\pi[|h_A(X_0) - \mathbf{1}_A|] &= \mathbb{E}_\pi[|h_A(X_0) - \mathbf{1}_A| \circ S^n] \\ &= \mathbb{E}_\pi[|h_A(\underbrace{X_0 \circ S^n}_{X_n}) - \underbrace{\mathbf{1}_A \circ S^n}_{\mathbf{1}_A}|] = \mathbb{E}_\pi[|h_A(X_n) - \mathbf{1}_A|].\end{aligned}\tag{3.2}$$

We now show that the rhs tends to 0. First, we find another expression for $h_A(X_n)$. Define $\mathcal{F}_n = \sigma(X_0, \dots, X_n)$. Then, $\mathbb{P}_\pi - a.s.$,

$$h_A(X_n) = \mathbb{E}_{X_n}[\mathbf{1}_A] \stackrel{(1)}{=} \mathbb{E}_\pi[\mathbf{1}_A \circ S^n | \mathcal{F}_n] \stackrel{(2)}{=} \mathbb{E}_\pi[\mathbf{1}_A | \mathcal{F}_n],$$

where $\stackrel{(1)}{=}$ comes from the Markov property and $\stackrel{(2)}{=}$ from the fact that $A \in \mathcal{I}$. Fix some $k \in \mathbb{N}$ and let $B \in \mathcal{F}_k$. Then, for all $n \geq k$, we have $\mathbb{E}[\mathbf{1}_B | \mathcal{F}_n] = \mathbf{1}_B$ and thus,

$$\mathbb{E}_\pi[|h_A(X_n) - \mathbf{1}_B|] = \mathbb{E}_\pi[|\mathbb{E}_\pi[\mathbf{1}_A - \mathbf{1}_B | \mathcal{F}_n]|] \leq \mathbb{E}_\pi[|\mathbf{1}_A - \mathbf{1}_B| | \mathcal{F}_n] = \mathbb{E}_\pi[|\mathbf{1}_B - \mathbf{1}_A|]$$

This implies, by using the triangular inequality and then taking the limsup,

$$\limsup_{n \rightarrow \infty} \mathbb{E}_\pi[|h_A(X_n) - \mathbf{1}_A|] \leq 2\mathbb{E}_\pi[|\mathbf{1}_B - \mathbf{1}_A|].$$

Now, according to the approximation lemma (Lemma 3.6), the rhs can be made arbitrarily small for a convenient choice of k and $B \in \mathcal{F}_k$. Therefore, $\lim_{n \rightarrow \infty} \mathbb{E}_\pi[|h_A(X_n) - \mathbf{1}_A|] = 0$. Combining this limiting result with (3.2), we deduce that $\mathbb{E}_\pi[|h_A(X_n) - \mathbf{1}_A|]$ is a constant that tends to 0 as n tends to infinity. It is thus equal to 0 for all $n \in \mathbb{N}$, and we have

$$h_A(X_0) = h_A(X_n) = \mathbf{1}_A, \quad \mathbb{P}_\pi - a.s.\tag{3.3}$$

- (ii) Now, define the probability measure π_A on (X, \mathcal{X}) by $\pi_A(f) = \frac{\mathbb{E}_\pi[h_A(X_0)f(X_0)]}{\mathbb{P}_\pi(A)}$ for any non-negative measurable function f on X . Then, using the Markov property, (3.3) with $n = 1$ and $X_1 \stackrel{\mathcal{L}}{=} X_0$ under \mathbb{P}_π (that is, they share the same distribution under \mathbb{P}_π), we get

$$\begin{aligned}\mathbb{E}_\pi [h_A(X_0) \times Pf(X_0)] &= \mathbb{E}_\pi [h_A(X_0) \times f(X_1)] = \mathbb{E}_\pi [h_A(X_1) \times f(X_1)] \\ &= \mathbb{E}_\pi [h_A(X_0) \times f(X_0)],\end{aligned}$$

Therefore, $\pi_A P(f) = \pi_A(Pf) = \pi_A(f)$, showing that π_A is an invariant probability measure for P and thus, $\pi = \pi_A$. Then,

$$\mathbb{P}_\pi(A) = \int_{\mathbf{X}} \pi(dx) \mathbb{P}_x(A) = \pi(h_A) = \pi_A(h_A) = \frac{\mathbb{E}_\pi [h_A(X_0) \times h_A(X_0)]}{\mathbb{P}_\pi(A)}.$$

Applying again (3.3) yields $\mathbb{P}_\pi(A) = \mathbb{E}_\pi [\mathbf{1}_A \times \mathbf{1}_A] / \mathbb{P}_\pi(A) = 1$ which completes the proof of the theorem. \square

As a consequence, the Birkhoff theorem for dynamical systems, Theorem 3.4, yields

Theorem 3.8. *Let P be a Markov kernel admitting a unique invariant probability measure π . Then, for all $h \in \mathbb{F}(\mathbf{X}^{\mathbb{N}})$ such that $\mathbb{E}_\pi[|h|] < \infty$, we have*

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} h(X_{k:\infty}) = \mathbb{E}_\pi[h], \quad \mathbb{P}_\pi - a.s.$$

or equivalently,

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} h \circ S^k = \mathbb{E}_\pi[h], \quad \mathbb{P}_\pi - a.s.$$

A particular case of Theorem 3.8 is when $h(X_{0:\infty}) = f(X_0)$. In such case, we have the following corollary.

Corollary 3.9. *Let P be a Markov kernel admitting a unique invariant probability measure π . Then, for all $f \in \mathbb{F}(\mathbf{X})$ such that $\pi(|f|) = \int_{\mathbf{X}} \pi(dx) |f(x)| < \infty$, we have*

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f), \quad \mathbb{P}_\pi - a.s. \quad (3.4)$$

The limiting result (3.4) is nice but it holds $\mathbb{P}_\pi - a.s.$ We now try to overcome this issue. Under the assumptions of Corollary 3.9, set $A = \left\{ \lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) - \pi(f) \right\}$. Combining Theorem 3.8 with (1.2), $0 = \mathbb{P}_\pi(A^c) = \int_{\mathbf{X}} \pi(dx) \mathbb{P}_x(A^c)$ and this implies that $\mathbb{P}_x(A^c) = 0$ (i.e. $\mathbb{P}_x(A) = 1$) for π -almost all $x \in \mathbf{X}$. Therefore, we finally get:

Corollary 3.10. *Let P be a Markov kernel admitting a unique invariant probability measure π . Then, for all $f \in \mathbb{F}(\mathbf{X})$ such that $\pi(|f|) = \int_{\mathbf{X}} \pi(dx) |f(x)| < \infty$, we have for π -almost all $x \in \mathbf{X}$,*

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f), \quad \mathbb{P}_x - a.s. \quad (3.5)$$

What about Metropolis-Hastings algorithms? In Section 2.2.1, we have seen that π is the unique invariant probability measure for $P_{\langle \pi, Q \rangle}^{MH}$ provided that $Q(x, dy) = q(x, y) \lambda(dy)$ and

$\pi(dy) = \pi(y)\lambda(dy)$ with $q > 0$ and $\pi > 0$. Therefore, (3.4) and (3.5) hold. Actually we can have an even stronger result!!!

Theorem 3.11. *Let Q be a Markov kernel on $X \times \mathcal{X}$ and $\pi \in \mathbf{M}_1(X)$. Assume that $Q(x, dy) = q(x, y)\lambda(dy)$ and $\pi(dy) = \pi(y)\lambda(dy)$ where $q > 0$, $\pi > 0$ and λ is a σ -finite measure on (X, \mathcal{X}) . Then, the Markov chain $\{X_n : n \in \mathbb{N}\}$ with Markov kernel $P_{(\pi, Q)}^{MH}$, i.e. the Markov chain generated by the Metropolis-Hastings algorithm is such that: for all initial distributions $\nu \in \mathbf{M}_1(X)$ and all $f \in \mathbf{F}(X)$ such that $\pi(|f|) = \int_X \pi(dx)|f(x)| < \infty$,*

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f), \quad \mathbb{P}_\nu - a.s \quad (3.6)$$

Proof. Let $\nu \in \mathbf{M}_1(X)$. Set $A = \{\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f)\}$. From Section 2.2.1, we know that π is the unique invariant probability measure for $P_{(\pi, Q)}^{MH}$ and therefore by Corollary 3.9, $0 = \mathbb{P}_\pi(A^c) = \int_X \pi(dx)h_{A^c}(x) = \pi(h_{A^c})$ where we have set $h_{A^c}(x) = \mathbb{E}_x[\mathbf{1}_{A^c}]$. Fix an arbitrary $x \in X$. Since

$$\left(\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f) \right) \Leftrightarrow \left(\lim_{n \rightarrow \infty} n^{-1} \sum_{k=1}^n f(X_k) = \pi(f) \right),$$

the set $A \in \mathcal{I}$ and hence $A^c \in \mathcal{I}$ since \mathcal{I} is a σ -field. Then, using the Markov property and $\mathbf{1}_{A^c} \circ S = \mathbf{1}_{A^c}$, we obtain

$$P_{(\pi, Q)}^{MH} h_{A^c}(x) = \mathbb{E}_x[\mathbb{E}_{X_1}[\mathbf{1}_{A^c}]] = \mathbb{E}_x[\mathbb{E}_x[\mathbf{1}_{A^c} \circ S | \mathcal{F}_1]] = \mathbb{E}_x[\mathbf{1}_{A^c} \circ S] = \mathbb{E}_x[\mathbf{1}_{A^c}] = h_{A^c}(x).$$

This implies, by combining with (2.4)

$$h_{A^c}(x) = P_{(\pi, Q)}^{MH} h_{A^c}(x) = \int \frac{q(x, y)\alpha(x, y)}{\pi(y)} h_{A^c}(y)\pi(y)\lambda(dy) + \bar{\alpha}(x)h_{A^c}(x).$$

Since $q > 0$ and $\pi > 0$, we can easily check that $\alpha > 0$ and $\bar{\alpha}(x) < 1$ (check it carefully). The first term in the rhs is null since $\pi(h_{A^c}) = 0$. Therefore, $(1 - \bar{\alpha}(x))h_{A^c}(x) = 0$ and since $\bar{\alpha}(x) < 1$, we can conclude that $h_{A^c}(x) = \mathbb{E}_x[\mathbf{1}_{A^c}] = 0$. Finally, x being arbitrary, we obtain

$$\mathbb{P}_\nu(A^c) = \int_X \nu(dx)\mathbb{E}_x[\mathbf{1}_{A^c}] = 0,$$

and this is equivalent to $\mathbb{P}_\nu(\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f)) = 1$. The proof is concluded. \square

Theorem 3.11 is nice since the LLN holds \mathbb{P}_ν -a.s. for all starting distributions ν but the problem is that the result of Theorem 3.11 only concerns MH kernels. For a general kernel P , we have the nice following result.

Theorem 3.12. *If P is a Markov kernel on $X \times \mathcal{X}$ that admits a unique invariant probability measure π . Assume in addition that for all bounded functions h and all measures $\nu \in \mathbf{M}_1(X)$,*

$$\lim_{n \rightarrow \infty} \nu P^n h = \pi(h) \quad (3.7)$$

Then, for all initial distributions $\nu \in \mathbf{M}_1(X)$ and all $f \in \mathbf{F}(X)$ such that $\pi(|f|) = \int_X \pi(dx)|f(x)| < \infty$,

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f), \quad \mathbb{P}_\nu - a.s \quad (3.8)$$

Proof. We start as in the proof of Theorem 3.11. Let $\nu \in \mathcal{M}_1(X)$. Set $A = \{\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f)\}$. Since π is the unique invariant probability measure for P , we have, by Corollary 3.9, $0 = \mathbb{P}_\pi(A^c) = \int_X \pi(dx) h_{A^c}(x) = \pi(h_{A^c})$ where we have set $h_{A^c}(x) = \mathbb{E}_x[\mathbf{1}_{A^c}]$. As in the proof of Theorem 3.11, $A^c \in \mathcal{I}$. Moreover,

$$\nu P^n h_{A^c} = \mathbb{E}_\nu[h_{A^c}(X_n)] = \mathbb{E}_\nu[\mathbb{E}_{X_n}[\mathbf{1}_{A^c}]] \stackrel{(1)}{=} \mathbb{E}_\nu[\mathbb{E}_\nu[\mathbf{1}_{A^c} \circ S^n | \mathcal{F}_n]] \stackrel{(2)}{=} \mathbb{E}_\nu[\mathbf{1}_{A^c} \circ S^n] \stackrel{(3)}{=} \mathbb{P}_\nu(A^c)$$

where $\stackrel{(1)}{=}$ follows from the Markov property, $\stackrel{(2)}{=}$ is the tower property, and $\stackrel{(3)}{=}$ follows from $\mathbf{1}_{A^c} \circ S^n = \mathbf{1}_{A^c}$, since $A^c \in \mathcal{I}$.

Combined with (3.7), we get

$$\mathbb{P}_\nu(A^c) = \nu P^h h_{A^c} = \pi(h_{A^c}) = \int \pi(dx) \mathbb{E}_x[\mathbf{1}_{A^c}] = \mathbb{P}_\pi(A^c) = 0$$

Finally $\mathbb{P}_\nu(A^c) = 0$, that is $\mathbb{P}_\nu(A) = 1$, which is equivalent to

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f), \quad \mathbb{P}_\nu - a.s$$

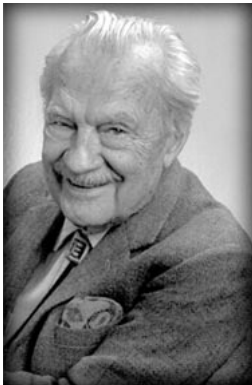
□

3.3 After studying this chapter...

- a) I understand that I can use the LLN (Law of Large Numbers) for any MH algorithm starting from anywhere...
- b) If I want to check a LLN, I first check if there is a unique invariant measure (Theorem 3.7)
- c) I understand the proof of Theorem 3.7, which is hard but so beautiful...

Highlights

3.A Nicholas Metropolis (source: wikipedia).



Nicholas Constantine Metropolis (June 11, 1915 – October 17, 1999) was a Greek-American physicist.

Metropolis received his BSc (1937) and PhD (1941) degrees in physics at the University of Chicago. Shortly afterwards, Robert Oppenheimer recruited him from Chicago, where he was at the time collaborating with Enrico Fermi and Edward Teller on the first nuclear reactors, to the Los Alamos National Laboratory. He arrived in Los Alamos in April 1943, as a member of the original staff of fifty scientists.

After World War II, he returned to the faculty of the University of Chicago as an assistant professor. He came back to Los Alamos in 1948 to lead the group in the Theoretical Division that designed and built the MANIAC I computer in 1952 that was modeled on the IAS machine, and the MANIAC II in 1957. (He chose the name MANIAC in the hope of stopping the rash of such acronyms for machine names, but may have, instead, only further stimulated such use.) (John von Neumann thought this acronym was too frivolous.) From 1957 to 1965 he was

Professor of Physics at the University of Chicago and was the founding Director of its Institute for Computer Research. In 1965 he returned to Los Alamos where he was made a Laboratory Senior Fellow in 1980.

In his memoirs, Stanislaw Ulam remembers that a small group, including himself, Metropolis, Calkin, Konopinski, Kistiakowsky, Teller and von Neumann, spent several evenings at Los Alamos playing poker. They played for very small sums, but: "Metropolis once described what a triumph it was to win ten dollars from John von Neumann, author of a famous treatise on game theory. He then bought his book for five dollars and pasted the other five inside the cover as a symbol of his victory." In another passage of his book, Ulam describes Metropolis as "a Greek-American with a wonderful personality."

3.B Wilfried Keith Hastings (source: Jeffrey Rosenthal's homepage).



The Metropolis-Hastings algorithm (or, Hastings-Metropolis algorithm) is the most common Markov chain Monte Carlo (MCMC) method. It is extremely widely used in applied statistics and in statistical physics and computer science and finance and more, to sample from complicated, high-dimensional probability distributions. A primary source for this algorithm is the paper:

- W.K. Hastings (1970), Monte Carlo sampling methods using Markov chains and their applications. *Biometrika* 57, 97-109.

This paper has been cited well over two thousand times -- a huge number. However, despite this paper's importance, very little information about W.K. Hastings himself is publicly available. The following brief biography is intended to (partially) answer that need.

W. Keith Hastings was born on July 21, 1930, in Toronto, Ontario, Canada. He received his B.A. in Applied Mathematics from the University of Toronto in 1953, and then worked from 1955-59 as a "Consultant in Computer Applications" for the Toronto company H.S. Gellman & Co. Hastings recalls:

Harvey Gellman was a good mentor and encouraged me to pursue my ideas. Some of the projects involved simulations and this was my first contact with statistics and generation of samples from probability distributions.

Overlapping somewhat with this, Hastings received his M.A. in 1958, and his Ph.D. in 1962, both from the University of Toronto's Department of Mathematics (which included Statistics at that time). His Ph.D. thesis title was "Invariant Fiducial Distributions". His Ph.D. supervisor was initially Don Fraser (who mentioned Hastings' thesis results in a 1962 letter to R.A. Fisher), and later Geoffrey Watson (while Fraser visited Stanford in 1961-62). After completing his Ph.D., Hastings worked briefly at the University of Canterbury in New Zealand (1962-64), and at Bell Labs in New Jersey (1964-66). Hastings writes:

I was never comfortable working on statistical inference for my thesis. My investigations led to too many dead ends and the work seemed to involve more mathematical considerations than statistical ones. When Geoff took over as my supervisor I briefly considered changing topics, but ended up sticking with my original topic and completed my thesis. In New Zealand, I continued this work for a while but eventually gave it up, the final blow coming when I learned that Fiducial Probability was declared 'dead' in a session during a statistics conference held in Ottawa. Bell Labs provided a welcome and effective antidote to all this as I gradually turned towards the computational aspects of statistics. In effect, I was then returning to my professional roots.

From 1966 to 1971, Hastings was an Associate Professor in the Department of Mathematics at the University of Toronto. During this period, he wrote the famous paper listed above (which generalised the work of N. Metropolis, A. Rosenbluth, M. Rosenbluth, A. Teller, and E. Teller (1953), "Equations of state calculations by fast computing machines", *J. Chem. Phys.* 21, 1087-1091). Hastings explains:

When I returned to the University of Toronto, after my time at Bell Labs, I focused on Monte Carlo methods and at first on methods of sampling from probability distributions with no particular

area of application in mind. [University of Toronto Chemistry professor] John Valleau and his associates consulted me concerning their work. They were using Metropolis's method to estimate the mean energy of a system of particles in a defined potential field. With 6 coordinates per particle, a system of just 100 particles involved a dimension of 600. When I learned how easy it was to generate samples from high dimensional distributions using Markov chains, I realised how important this was for Statistics, and I devoted all my time to this method and its variants which resulted in the 1970 paper.

While at the University of Toronto, Hastings also supervised his one Ph.D. student, Peter Peskun (now at York University), whose 1970 dissertation "The Choice Of Transition Matrix In Monte Carlo Sampling Methods Using Markov Chains" developed the Peskun ordering on Markov chain kernels. Peskun recalls:

Dr. Hastings was down to earth and very good natured. I can still picture him tugging at his waist band as he chuckled over some comment he had just made. It was a pleasure having Dr. Hastings as my Ph.D. supervisor. He never meddled in what I was trying to do but was always happy to hear and listen to any new results that I came up with. He did make one important suggestion to me which was to express my initial heuristic results in matrix form. This was of tremendous help in proving, in particular, Peskun orderings.

In 1971, Hastings joined the Department of Mathematics at the University of Victoria (in British Columbia, on the west coast of Canada) as an Associate Professor, and was granted tenure there in 1974. He taught at Victoria for 21 years, usually teaching six one-semester courses per year. He did not supervise any more Ph.D. students, but he did supervise two M.Sc. students, and serve on the committees of four Ph.D. and two M.Sc. students. He held NSERC research grants from 1969 to 1980. Hastings' C.V. lists only two other refereed research papers besides the famous (1970) one:

- W.K. Hastings (1972), Test Data for Statistical Algorithms: Least Squares and ANOVA. J. Amer. Statist. Assoc. 67, 874-879.
- W.K. Hastings (1974), Variance Reduction and Non-normality. Biometrika 61, 143-149.

It also lists one non-refereed publication ("Death and Taxes", American Studies in Papyrology 10, joint with A.E. Samuel, A.K. Bowman, and R.S. Bagnall), and a couple of memoranda for Bell Labs (including the suggestive-sounding "An Overview of Statistical Computing Software", 1966). Hastings retired from the University of Victoria in 1992. He passed away peacefully in Victoria on May 13, 2016, at the age of 85.

Chapter 4

Geometric ergodicity and Central Limit theorems

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Keywords: Geometric Ergodicity, Coupling, Poisson equation, Martingales, Central Limit theorem.

Let (X_n) be a Markov chain with Markov kernel P and assume that P admits an invariant probability measure π . In this chapter, we are interested in finding conditions under which we can have bound of the error between the marginal distribution of X_n and the distribution π . To do so, we first need to define some notion of "distance" between probability measures (we will define here the total variation distance). Then, we will compare π and $P^n(x, \cdot)$, the distribution of the n -th iterate of the Markov kernel starting from an arbitrary point $x \in X$, by bounding the total variation distance between them.

4.1 Total variation norm and coupling

We start with the notion of coupling between probability measures. In words, if μ, ν are two probability measures on (X, \mathcal{X}) , then a coupling γ of (μ, ν) is a probability measure on the product space $(X^2, \mathcal{X}^{\otimes 2})$ such that if $(X, Y) \sim \gamma$, then we have the marginal conditions: $X \sim \mu$ and $Y \sim \nu$.

Definition 4.1. Let (X, \mathcal{X}) be a measurable space and let ν, μ be two probability measures $\mu, \nu \in M_1(X)$. We define $\mathcal{C}(\mu, \nu)$, the coupling set associated to (μ, ν) as follows

$$\mathcal{C}(\mu, \nu) = \{ \gamma \in M_1(X^2) : \forall A \in \mathcal{X}, \gamma(A \times X) = \mu(A), \gamma(X \times A) = \nu(A) \}$$

Any $\gamma \in \mathcal{C}(\mu, \nu)$ is called a coupling of (μ, ν) .

Just to play with the definition of coupling, you can for example construct a coupling of (μ, μ) by sampling $X \sim \mu$ and by setting $Y = X$. The distribution of (X, Y) is then a coupling of (μ, μ) . This is a very "dependent" coupling (since we chose $X = Y$ by construction). We can also construct an "independent" coupling as follows: draw independently X and Y according to the same distribution μ , then the distribution of (X, Y) is a coupling of (μ, μ) (since $X \sim \mu$ and $Y \sim \mu$).

But then, which coupling is interesting? As we shall see in what follows, there is a real degree of freedom for choosing an adequate coupling. We will present some useful couplings but there is no general rule.

Before going further into coupling techniques, let us define the total variation norm and let us link it with coupling.

Definition 4.2. Let (X, \mathcal{X}) be a measurable space and let ν, μ be two probability measures $\mu, \nu \in \mathcal{M}_1(X)$. Then the total variation norm between μ and ν noted $\|\mu - \nu\|_{\text{TV}}$, is defined by

$$\|\mu - \nu\|_{\text{TV}} = 2 \sup \{ |\mu(f) - \nu(f)| : f \in \mathcal{F}(X), 0 \leq f \leq 1 \} \quad (4.1)$$

$$= \int |\varphi_0 - \varphi_1|(x) \zeta(dx) \quad (4.2)$$

$$= 2 \inf \{ \mathbb{P}(X \neq Y) : (X, Y) \sim \gamma \text{ where } \gamma \in \mathcal{C}(\mu, \nu) \} \quad (4.3)$$

where $\mu(dx) = \varphi_0(x)\zeta(dx)$ and $\nu(dx) = \varphi_1(x)\zeta(dx)$.

Before showing that these different expressions of the total variation are indeed equivalent, let us make a few comments.

- (a) The reader might wonder why we can always write $\mu(dx) = \varphi_0(x)\zeta(dx)$ and $\nu(dx) = \varphi_1(x)\zeta(dx)$ for some well-chosen measure ζ , and measurable functions φ_0 and φ_1 . Actually, if we take $\mu, \nu \in \mathcal{M}_1(X)$, then setting $\zeta = \mu + \nu$ yields the two implications:

$$(\zeta(A) = 0) \implies (\mu(A) = 0) \quad \text{and} \quad (\zeta(A) = 0) \implies (\nu(A) = 0)$$

Therefore, the measure ζ dominates the measure μ and it also dominates the measure ν . By the Radon Nikodym theorem, the measures μ and ν have densities wrt ζ , densities that we call φ_0 and φ_1 in Definition 4.2.

- (b) The first definition, (4.1), is expressed as a supremum over functions, while the last one is an infimum over coupling measures... These two equalities can thus be considered as a *duality formula*.
- (c) The expression in the middle allows to write the total variation as a L_1 -norm between the two densities of the distributions wrt to a common dominating measure.
- (d) An immediate consequence of the equivalent definitions of the total variation norm is that if f is a measurable function taking values in $[0, 1]$ and if X, Y are random variables such that $(X, Y) \sim \gamma$ with $\gamma \in \mathcal{C}(\mu, \nu)$, then we have the coupling inequality

$$|\mu(f) - \nu(f)| \leq \mathbb{P}(X \neq Y)$$

This inequality will often be used in practice. It is due to such inequalities that coupling techniques are so successful.

Proof of the equivalences in Definition 4.2. Call A, B and C the quantities that appear respectively in (4.1), (4.2) and (4.3). Any function f satisfies $0 \leq f \leq 1$ if and only if the function $g = 2f - 1$ satisfies $|g| \leq 1$. This implies immediately

$$A = 2 \sup \{ |\mu(f) - \nu(f)| : f \in \mathbf{F}(\mathbf{X}), 0 \leq f \leq 1 \} = \sup \{ |\mu(g) - \nu(g)| : g \in \mathbf{F}(\mathbf{X}), |g| \leq 1 \}$$

Moreover, for any $g \in \mathbf{F}(\mathbf{X})$ such that $|g| \leq 1$,

$$|\mu(g) - \nu(g)| = \left| \int (\varphi_1 - \varphi_0)(x)g(x)\zeta(dx) \right| \leq \int |\varphi_1 - \varphi_0|(x) \underbrace{|g(x)|}_{\leq 1} \zeta(dx) = B$$

Therefore, $A \leq B$. Moreover, setting $g^*(x) = \text{sign}(\varphi_0(x) - \varphi_1(x))$, we have $|g^*| = 1$ and therefore,

$$\begin{aligned} B &= \int |\varphi_0 - \varphi_1|(x)\zeta(dx) = \int (\varphi_0(x) - \varphi_1(x))g^*(x)\zeta(dx) \\ &= \mu(g^*) - \nu(g^*) \leq \sup \{ |\mu(g) - \nu(g)| : g \in \mathbf{F}(\mathbf{X}), |g| \leq 1 \} = A \end{aligned}$$

Thus $\boxed{A = B}$. Now let $f \in \mathbf{F}(\mathbf{X})$ be such that $0 \leq f \leq 1$ and let X, Y be random variables such that $(X, Y) \sim \gamma$ with $\gamma \in \mathcal{C}(\mu, \nu)$, then

$$|\mu(f) - \nu(f)| = |\mathbb{E}[f(X) - f(Y)]| = |\mathbb{E}[\{f(X) - f(Y)\} \mathbf{1}_{X \neq Y}]| \leq \underbrace{\mathbb{E}[|f(X) - f(Y)| \mathbf{1}_{X \neq Y}]}_{\leq 1} \leq \mathbb{P}(X \neq Y)$$

This shows that $\boxed{A \leq C}$. To finish the proof, we will show that $C \leq B$ and to do so, we will exhibit an **optimal coupling** of (μ, ν) .

Define

$$\epsilon = \int_{\mathbf{X}} \varphi_0 \wedge \varphi_1(x)\zeta(dx) \quad \text{and} \quad \zeta'(dx) = \frac{\varphi_0 \wedge \varphi_1(x)}{\epsilon} \zeta(dx)$$

Then, it can be readily checked that $\zeta' \in \mathbf{M}_1(\mathbf{X})$, and $\mu(dx) \geq \epsilon\zeta'(dx)$ and $\nu(dx) \geq \epsilon\zeta'(dx)$. This implies that there exist $\mu_1, \nu_1 \in \mathbf{M}_1(\mathbf{X})$ such that

$$\begin{aligned} \mu(dx) &= \epsilon\zeta'(dx) + (1 - \epsilon)\mu_1(dx) \\ \nu(dx) &= \epsilon\zeta'(dx) + (1 - \epsilon)\nu_1(dx) \end{aligned}$$

Define $\gamma(dx dy) = \epsilon\zeta'(dx)\delta_x(dy) + (1 - \epsilon)\mu_1(dx)\nu_1(dy)$. Obviously, $\gamma \in \mathcal{C}(\mu, \nu)$. Let X, Y be two random variables such that $(X, Y) \sim \gamma$. We can draw (X, Y) in the following way: draw a Bernoulli variable $U \sim \text{Ber}(\epsilon)$. If $U = 1$, draw $X \sim \zeta'$ and set $Y = X$. If $U = 0$, then draw independently $X \sim \mu_1$ and $Y \sim \nu_1$. Then, clearly

$$\begin{aligned} \mathbb{P}(X \neq Y) &= 1 - \mathbb{P}(X = Y) \leq 1 - \epsilon = 1 - \int_{\mathbf{X}} \varphi_0 \wedge \varphi_1(x)\zeta(dx) \\ &= \frac{1}{2} \int_{\mathbf{X}} \underbrace{\varphi_0 + \varphi_1(x) - 2\varphi_0 \wedge \varphi_1(x)}_{|\varphi_0 - \varphi_1(x)|} \zeta(dx) \end{aligned}$$

This shows that $\boxed{C \leq B}$ and the proof is completed. \square

Exercise 4.3. Show that the supremum in (4.1) is attained with a convenient choice of f .

Another equivalent expression of the total variation distance is

$$\|\mu - \nu\|_{\text{TV}} = 2 \inf \{ \gamma(\Delta) : \gamma \in \mathcal{C}(\mu, \nu) \} \quad (4.4)$$

where we have used the notation $\Delta(x, y) = \mathbf{1}_{x \neq y}$ (we also say that $\Delta(x, y)$ is the Hamming distance between x and y).

Example 4.4. See Figure 4.1. Let $\mu = \mathcal{N}(-1, 1)$ and $\nu = \mathcal{N}(1, 1)$. Let $X \sim \mathcal{N}(-1, 1)$ and set $Y = X + 2$. Then, (X, Y) is a coupling of (μ, ν) but it is not the optimal coupling for the Hamming distance since $\mathbb{P}(X \neq Y) = 1$, whereas using Definition 4.2,

$$\|\mu - \nu\|_{\text{TV}} = 2 \left(1 - \int_{-\infty}^{\infty} \phi(x+1) \wedge \phi(x-1) dx \right) = 2 \left(1 - 2 \int_1^{\infty} \frac{e^{-u^2/2}}{\sqrt{2\pi}} du \right),$$

where ϕ the density of the standard Gaussian distribution.

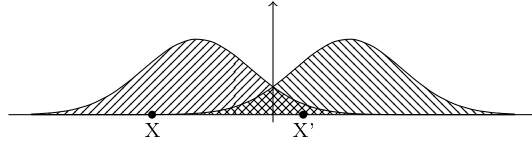


Fig. 4.1 An example of coupling of two probability measures.

4.2 Geometric ergodicity

In what follows, we assume that for **some measurable function** $V : X \rightarrow [1, \infty)$, we have

(A1) [**Minorizing condition**] for all $d > 0$, there exists $\epsilon_d > 0$ and a probability measure ν_d such that

$$\forall x \in C_d := \{V \leq d\}, \quad P(x, \cdot) \geq \epsilon_d \nu_d(\cdot) \quad (4.5)$$

(A2) [**Drift condition**] there exists a constants $(\lambda, b) \in (0, 1) \times \mathbb{R}^+$ such that for all $x \in X$,

$$PV(x) \leq \lambda V(x) + b$$

Typically, the function V is unbounded (but in particular situations, it can also be bounded) and the level set $\{V \leq d\}$ is typically compact (when the chain takes value a topological space)... Roughly speaking, (A1) tells you that wherever x moves in a set C_d , the measure $P(x, \cdot)$ is lower bounded by the non-trivial measure $\epsilon_d \nu_d(\cdot)$. In many cases, $X = \mathbb{R}^n$, and P is dominated by the Lebesgue measure: $P(x, dy) = p(x, y)dy$. In that case, we usually take $P(x, A) \geq \epsilon_d \nu_d(A)$ where

$$\epsilon_d = \int_X \left[\inf_{x \in C_d} p(x, y) \right] dy, \quad \nu_d(A) = \frac{\int_A \inf_{x \in C_d} p(x, y) dy}{\epsilon_d}$$

i.e. we only need to bound from below the kernel density $p(x, y)$ when $x \in C_d$. If C_d is compact, then it is quite easy to check such lower-bound. In the Markov chain terminology, if (4.5) holds, we say that C_d is a small set.

The drift condition (A2) tells you that in the mean sense, the drift function V is shrunk by a factor λ up to the additive constant b ... Intuitively speaking, the Markov kernel P does not bring to regions where V is too large so that the chain does not go to infinity too quickly (since limited values of V corresponds typically to bounded sets). And we can easily imagine that such chains will have nice ergodic properties.

Before stating the result, we must say that, in practise, for a given Markov kernel P , there is no general rule for guessing the expression of a drift function V that satisfies (A2), and we have to try different functions V for checking the assumptions... For example, if $X_{k+1} = \alpha X_k + \epsilon_k$ where (ϵ_k) are iid and $\alpha \in (0, 1)$. If we know that $\mathbb{E}[|\epsilon_1|^r] < \infty$, then we can try a drift function $V(x) = |x|^r$ and if $\mathbb{E}[e^{\beta \epsilon_1}] < \infty$, then we can try $V(x) = e^{\beta x}$. For MH algorithms, we also sometimes use a negative power of the target density. But once again, the choice of V is very model specific (and in some sense, this is a good opportunity to be imaginative!!!). We now show that assumptions (A1) and (A2) imply that the Markov kernel P is "geometrically ergodic" in the following sense.

Theorem 4.5. [Geometric ergodicity] Assume (A1) and (A2) for some measurable function $V \geq 1$. Then, there exists a constant $\varrho \in (0, 1)$ such that for all $x, x' \in \mathsf{X}$ and all $n \in \mathbb{N}$,

$$\|P^n(x, \cdot) - P^n(x', \cdot)\|_{\text{TV}} \leq \varrho^n [V(x) + V(x')].$$

Remark 4.6. Assume that there exist a constant $\epsilon > 0$ and a probability measure ν such that for all $x \in \mathsf{X}$, $P(x, \cdot) \geq \epsilon\nu(\cdot)$. In that case, (A1) and (A2) are satisfied with the constant function $V(x) = 1$ and Theorem 4.5 then shows that

$$\|P^n(x, \cdot) - P^n(x', \cdot)\|_{\text{TV}} \leq 2\varrho^n.$$

for some constant $\varrho \in (0, 1)$. Such a Markov chain is usually said to be uniformly ergodic.

The proof needs several steps. To bound $\|P^n(x, \cdot) - P^n(x', \cdot)\|_{\text{TV}}$, we will construct a bivariate Markov chain (X_k, X'_k) such that first component process (X_k) behaves marginally as a Markov chain starting from x with Markov kernel P , while the second component process (X'_k) behaves marginally as a Markov chain starting from x' with Markov kernel P . Let us be more specific... In what follows, we choose d sufficiently large so that

$$\bar{\lambda} := \lambda + \frac{2b}{1+d} < 1 \quad (4.6)$$

Definition of the joint kernel \bar{P}

Define $Q(x_k, dx_{k+1}) = \frac{P(x_k, dx_{k+1}) - \epsilon_d \nu_d(dx_{k+1})}{1 - \epsilon_d}$ and set

$$\begin{aligned} \bar{P}((x_k, x'_k), dx_{k+1} dx'_{k+1}) &= \mathbf{1}_{x_k = x'_k} P(x_k, dx_{k+1}) \delta_{x_{k+1}}(x'_{k+1}) \\ &+ \mathbf{1}_{x_k \neq x'_k} \mathbf{1}_{(x_k, x'_k) \notin C_d^2} [P(x_k, dx_{k+1}) P(x'_k, dx'_{k+1})] \\ &+ \mathbf{1}_{x_k \neq x'_k} \mathbf{1}_{(x_k, x'_k) \in C_d^2} [\epsilon_d \nu_d(dx_{k+1}) \delta_{x_{k+1}}(x'_{k+1}) + (1 - \epsilon_d) Q(x_k, dx_{k+1}) Q(x'_k, dx'_{k+1})] \end{aligned}$$

Actually, \bar{P} is a Markov kernel on $\mathsf{X}^2 \times \mathcal{X}^{\otimes 2}$ and it can be easily checked that

$$\bar{P}((x, x'), \cdot) \in \mathcal{C}(P(x, \cdot), P(x', \cdot)) \quad (4.7)$$

This will indeed imply by induction that for any $n \in \mathbb{N}$,

$$\bar{P}^n((x, x'), \cdot) \in \mathcal{C}(P^n(x, \cdot), P^n(x', \cdot)) \quad (4.8)$$

Interpretation of the joint kernel \bar{P}

Set $\bar{X}_k = (X_k, X'_k)$ and $\bar{C}_d = C_c \times C_d$. If $(\bar{X}_k)_{k \in \mathbb{N}}$ is a Markov chain with the Markov kernel \bar{P} , the transition from $\bar{X}_k = (x_k, x'_k)$ to $\bar{X}_{k+1} = (X_{k+1}, X'_{k+1})$ can be seen as follows

- If $x_k = x'_k$, draw $X_{k+1} \sim P(x_k, \cdot)$ and set $X'_{k+1} = X_{k+1}$.
- Otherwise,
 - If $(x_k, x'_k) \notin \bar{C}_d$, then
 - Draw independently $X_{k+1} \sim P(x_k, \cdot)$ and $X'_{k+1} \sim P(x'_k, \cdot)$
 - If $(x_k, x'_k) \in \bar{C}_d$, then
 - Draw $U \sim \text{Ber}(\epsilon_d)$.

- If $U = 1$, draw $X_{k+1} \sim \nu_d$ and set $X'_{k+1} = X_{k+1}$.
- If $U = 0$, draw independently $X_{k+1} \sim Q(x_k, \cdot)$ and $X'_{k+1} \sim Q(x'_k, \cdot)$.

- Set $\bar{X}_{k+1} = (X_{k+1}, X'_{k+1})$.

Therefore, the bivariate Markov chain $(\bar{X}_k)_{k \in \mathbb{N}} = (X_k, X'_k)_{k \in \mathbb{N}}$ is such that it tries to couple its two components with probability ϵ_d each time it falls into \bar{C}_d and once it couples (ie $X_k = X'_k$) then, it stays together for ever (ie for all $n \geq k$, $X_n = X'_n$).

Some nice properties of \bar{P}

The following inequalities are immediate:

1. Set $\Delta(x, x') = \mathbf{1}_{x \neq x'}$, then
 - (a) if $(x, x') \in \bar{C}_d$, $\bar{P}\Delta(x, x') \leq (1 - \epsilon_d)\Delta(x, x')$
 - (b) if $(x, x') \notin \bar{C}_d$, $\bar{P}\Delta(x, x') \leq \Delta(x, x')$
2. Setting $\bar{V}(x, x') = (V(x) + V(x'))/2$, we have $\bar{P}\bar{V}(x, x') = 2^{-1}(PV(x) + PV(x')) \leq \lambda\bar{V}(x, x') + b$. This implies
 - (a) if $(x, x') \in \bar{C}_d$, $\bar{P}\bar{V}(x, x') \leq (\lambda + b)\bar{V}(x, x')$
 - (b) if $(x, x') \notin \bar{C}_d$, $\bar{P}\bar{V}(x, x') \leq \underbrace{\left(\lambda + \frac{2b}{1+d}\right)}_{\bar{\lambda}}\bar{V}(x, x')$

We now have all the tools for proving Theorem 4.5.

of Theorem 4.5. For any $\beta \in (0, 1)$, define

$$\varrho_\beta = \max((1 - \epsilon_d)^{1-\beta}(\lambda + b)^\beta, \bar{\lambda}^\beta) \quad (4.9)$$

The expression of ϱ_β may seem a bit complicated (we will understand why we choose ϱ_β like this in (4.10) below) but, since $\bar{\lambda}$ and $1 - \epsilon_d$ are both in $(0, 1)$, we can always pick β sufficiently small (but positive) so that $\varrho_\beta \in (0, 1)$.

This ϱ_β being chosen, set $W = \Delta^{1-\beta}\bar{V}^\beta$. Then, using Holder's inequality and the inequalities in the section **Some nice properties of \bar{P}** , we have for all $(x, x') \in \mathbb{X}^2$,

$$\begin{aligned} \bar{P}W(x, x') &= \bar{P}(\Delta^{1-\beta}\bar{V}^\beta)(x, x') \leq (\bar{P}\Delta(x, x'))^{1-\beta}(\bar{P}\bar{V}(x, x'))^\beta \\ &\leq (\Delta^{1-\beta}\bar{V}^\beta)(x, x') \times \begin{cases} (1 - \epsilon_d)^{1-\beta}(\lambda + b)^\beta & \text{if } (x, x') \in C_d^2 \\ \bar{\lambda}^\beta & \text{if } (x, x') \notin C_d^2 \end{cases} \\ &\leq \varrho_\beta W(x, x') \end{aligned}$$

This implies by induction that for all $n \in \mathbb{N}$ and all $(x, x') \in \mathbb{X}^2$,

$$\bar{P}^n W(x, x') \leq \varrho_\beta^n W(x, x') \quad (4.10)$$

Then

$$\|P^n(x, \cdot) - P^n(x', \cdot)\|_{\text{TV}} \stackrel{(1)}{\leq} 2\bar{P}^n \Delta(x, x') \stackrel{(2)}{\leq} 2\bar{P}^n W(x, x') \stackrel{(3)}{\leq} 2\varrho_\beta^n W(x, x') \stackrel{(4)}{\leq} \varrho_\beta^n (V(x) + V(x'))$$

where (1) comes from (4.8) and (4.4), (2) from $\Delta(x, x') = \Delta^{1-\beta}(x, x') \leq W(x, x')$ because $V \geq 1$, (3) from (4.10) and (4) from

$$W(x, x') \leq \left(\frac{V(x) + V(x')}{2}\right)^\beta \leq \frac{V(x) + V(x')}{2}$$

since $V \geq 1$ and $\beta \in (0, 1)$. □

Corollary 4.7. *Assume that (A1) and (A2) hold for some measurable function $V \geq 1$. Then, the Markov kernel P admits a unique invariant probability measure π . Moreover, $\pi(V) < \infty$ and there exists constants $(\varrho, \alpha) \in (0, 1) \times \mathbb{R}^+$ such that for all $\mu \in \mathbb{M}_1(\mathbb{X})$ and all $n \in \mathbb{N}$,*

$$\|\mu P^n - \pi\|_{\text{TV}} \leq \alpha \varrho^n \mu(V).$$

Proof. For any $\mu, \nu \in \mathbf{M}_1(\mathbf{X})$ and any $h \in \mathbf{F}(\mathbf{X})$ such that $|h| \leq 1$, we have, using Theorem 4.5,

$$|\mu P^n h - \nu P^n h| = \left| \int_{\mathbf{X}^2} \mu(dx) \nu(dy) [P^n h(x) - P^n h(y)] \right| \leq \int_{\mathbf{X}^2} \mu(dx) \nu(dy) |[P^n h(x) - P^n h(y)]| \leq \varrho^n [\mu(V) + \nu(V)]$$

Thus,

$$\|\mu P^n - \nu P^n\|_{\text{TV}} \leq \varrho^n [\mu(V) + \nu(V)] \quad (4.11)$$

Replacing μ by δ_x and ν by $P(x, \cdot)$, we get for all $x \in \mathbf{X}$,

$$\|P^n(x, \cdot) - P^{n+1}(x, \cdot)\|_{\text{TV}} \leq \varrho^n [V(x) + PV(x)] \leq \varrho^n [(1 + \lambda)V(x) + b]$$

This implies that $\{P^n(x, \cdot)\}$ is a Cauchy sequence and since $(\mathbf{M}_1(\mathbf{X}), \|\cdot\|_{\text{TV}})$ is complete, it converges to a limit $\pi \in \mathbf{M}_1(\mathbf{X})$. Then, for all $x \in \mathbf{X}$ and all $h \in \mathbf{F}(\mathbf{X})$ such that $|h| \leq 1$, we also have $|Ph| \leq 1$ and therefore

$$\pi(Ph) = \lim_{n \rightarrow \infty} P^n(Ph)(x) = \lim_{n \rightarrow \infty} P^{n+1}h(x) = \pi(h)$$

showing that π is *P-invariant*. We now show *uniqueness* of an invariant probability measure. To see this, note that π actually does not depend on the choice of x . Indeed, replacing μ by δ_x and ν by $\delta_{x'}$ in (4.11), we get that $\lim_{n \rightarrow \infty} \|P^n(x, \cdot) - P^n(x', \cdot)\|_{\text{TV}} = 0$. Therefore, for all $x \in \mathbf{X}$, $\lim_{n \rightarrow \infty} P^n h(x) = \pi(h)$. Let π' be an invariant probability measure for P , then

$$\pi'(h) = \pi' P^n(h) = \int \pi'(dx) \underbrace{P^n h(x)}_{\rightarrow \pi(h)} \rightarrow_{n \rightarrow \infty} \pi(h)$$

where the last equality comes from Lebesgue's dominated convergence theorem. Since $PV \leq \lambda V + b$, we have by induction for all $n \in \mathbb{N}$,

$$P^n V(x) \leq \lambda^n V(x) + b \left(\sum_{k=0}^{n-1} \lambda^k \right) \leq \lambda^n V(x) + \frac{b}{1 - \lambda}$$

Therefore, for any $M > 0$, by Jensen's inequality applied to the convex function $u \mapsto u \wedge M$, we have $P^n(V \wedge M)(x) \leq (P^n V(x)) \wedge M \leq \left(\lambda^n V(x) + \frac{b}{1 - \lambda} \right) \wedge M$. We then integrate wrt π and use $\pi = \pi P^n$:

$$\pi(V \wedge M) = \pi P^n(V \wedge M) \leq \int \pi(dx) \left(\lambda^n V(x) + \frac{b}{1 - \lambda} \right) \wedge M$$

The Lebesgue dominated convergence theorem then shows by letting n to infinity, $\pi(V \wedge M) \leq \frac{b}{1 - \lambda} \wedge M$. Then, letting M to infinity, we get $\pi(V) \leq b/(1 - \lambda) < \infty$. To complete the proof, apply (4.11) with $\nu = \pi$, we get

$$\|\mu P^n - \underbrace{\pi P^n}_{\pi}\|_{\text{TV}} \leq \varrho^n [\mu(V) + \pi(V)] \leq \alpha \varrho^n \mu(V)$$

with $\alpha = 1 + \pi(V) < \infty$. □

Exercise 7.12 shows that under (A1) and (A2) a Law of Large number is valid, starting from any initial distribution.

Theorem 4.7 is nice but it is expressed only as a bound on the total variation norm, this implies that we can bound $|\mu P^n h - \pi(h)|$ where $|h| \leq 1$. Under the same assumptions, we can actually obtain more general bounds for possibly unbounded functions h . The proof is slightly more complicated so we decide to just state the result.

Theorem 4.8. *Assume that (A1) and (A2) hold for some function $V \geq 1$. Then, there exist constants $(\varrho, \alpha) \in (0, 1) \times \mathbb{R}^+$ such that for all $\mu \in \mathbf{M}_1(\mathbf{X})$ satisfying $\mu(V) < \infty$, all $n \in \mathbb{N}$ and all measurable functions $|h| \leq V$,*

$$|\mu P^n h - \pi(h)| \leq \alpha \varrho^n \mu(V).$$

4.3 The Poisson Equation

4.3.1 Definition

We start with a general definition of a Poisson equation.

Definition 4.9. For a given measurable function h such that $\pi|h| < \infty$, the Poisson equation is defined by

$$\hat{h} - P\hat{h} = h - \pi(h) \quad (4.12)$$

A solution to Poisson equation (4.12) is a function \hat{h} such that $P|\hat{h}|(x) < \infty$ for all $x \in \mathsf{X}$ and for all $x \in \mathsf{X}$, $\hat{h}(x) - P\hat{h}(x) = h(x) - \pi(h)$.

The following result holds under the set of assumptions (A1) and (A2).

Theorem 4.10. Assume (A1) and (A2) hold for some measurable function $V \geq 1$. Then, for any function h such that $|h| \leq V$, the function

$$\hat{h} = \sum_{n=0}^{\infty} \{P^n h - \pi(h)\} \quad (4.13)$$

is well-defined. Moreover, \hat{h} is a solution of the Poisson equation associated to h and there exists a constant γ such that for all $x \in \mathsf{X}$,

$$|\hat{h}(x)| \leq \gamma V(x)$$

Proof. To see the existence of a solution to the Poisson equation under (A1) and (A2), note that by Theorem 4.8, $\sum_{n=0}^{\infty} \{P^n h(x) - \pi(h)\}$ converges for any $|h| \leq V$ and we can thus define

$$\hat{h}(x) = \sum_{n=0}^{\infty} \{P^n h(x) - \pi(h)\}$$

Then,

$$P\hat{h}(x) = \sum_{n=1}^{\infty} \{P^n h(x) - \pi(h)\}$$

which immediately shows (4.12). Moreover, setting \hat{h} as in (4.13), Theorem 4.8 shows that for all $x \in \mathsf{X}$,

$$|\hat{h}(x)| \leq \frac{\alpha}{1-\varrho} V(x)$$

□

4.3.2 Poisson equation and martingales

The interest of Poisson equation is that it allows to link quantities of interest of our Markov chain with a well-chosen martingale. Then, we apply limiting results on martingales and the impact of those results to our Markov chain.

We start with a refresher on martingales.

4.3.2.1 A refresh on martingales

Let $(M_n)_{n \in \mathbb{N}}$ be a sequence of random variables on the same probability space $(\Omega, \mathcal{F}, \mathbb{P})$ and let $(\mathcal{F}_n)_{n \in \mathbb{N}}$ be a filtration (ie for all $n \in \mathbb{N}$, $\mathcal{F}_n \subset \mathcal{F}_{n+1} \subset \mathcal{F}$). We say that $(M_n)_{n \in \mathbb{N}}$ is a (\mathcal{F}_n) -martingale if for all $n \in \mathbb{N}$, M_n is integrable and for all $n \geq 1$,

$$\mathbb{E}[M_n | \mathcal{F}_{n-1}] = M_{n-1}$$

The *increment process* of the martingale is by definition $(M_{n+1} - M_n)_{n \in \mathbb{N}}$.

The following CLT result holds for martingales with stationary increments. It is stated without proof.

Theorem 4.11. *If a sequence $(M_n)_{n \in \mathbb{N}}$ is a (\mathcal{F}_n) -martingale with stationary and square integrable increments, then*

$$n^{-1/2} M_n \xrightarrow{\mathcal{L}^s} \mathcal{N}(0, \mathbb{E}[(M_1 - M_0)^2])$$

4.3.2.2 Link with martingales

Define

$$S_n(h) = \sum_{k=0}^{n-1} \{h(X_k) - \pi(h)\}$$

The solution of the Poisson equation allows us to relate $S_n(h)$ to a martingale by writing:

$$S_n(h) = M_n(\hat{h}) + \hat{h}(X_0) - \hat{h}(X_n) \quad (4.14)$$

where

$$M_n(\hat{h}) = \sum_{k=1}^n \left\{ \hat{h}(X_k) - P\hat{h}(X_{k-1}) \right\} \quad (4.15)$$

Note that $\left\{ M_n(\hat{h}) \right\}_{n \in \mathbb{N}}$ is indeed a (\mathcal{F}_k) -martingale where $\mathcal{F}_k = \sigma(X_0, \dots, X_k)$ since:

$$\mathbb{E}[M_n(\hat{h}) | \mathcal{F}_{n-1}] - M_{n-1}(h) = \mathbb{E}[\hat{h}(X_n) - P\hat{h}(X_{n-1}) | \mathcal{F}_{n-1}] = P\hat{h}(X_{n-1}) - P\hat{h}(X_{n-1}) = 0$$

This link with martingales allows to obtain LLN and Central Limit theorems for our Markov chain from limiting results on martingales. Since LLN has been already studied in a different approach in the previous chapter, we only focus here on CLT.

4.3.3 Central Limit theorems

Theorem 4.12. *Let P be a Markov kernel with a unique invariant probability measure π . Let $h \in L_2(\pi)$. Assume that there exists a solution $\hat{h} \in L_2(\pi)$ to the Poisson equation $\hat{h} - P\hat{h} = h$. Then*

$$n^{-1/2} \sum_{k=0}^{n-1} \{h(X_k) - \pi(h)\} \xrightarrow{\mathcal{L}_{\mathbb{P}_\pi}^{\mathcal{L}_{\mathbb{P}_\pi}} \mathcal{N}(0, \sigma_\pi^2(h)),$$

where

$$\sigma_\pi^2(h) = \mathbb{E}_\pi[\{\hat{h}(X_1) - P\hat{h}(X_0)\}^2] \quad (4.16)$$

Proof. Without loss of generality, we assume $\pi(h) = 0$. The sequence $(M_n(\hat{h}))_{n \in \mathbb{N}}$ defined in (4.15) is such that

$$\begin{aligned} \mathbb{E}_\pi[(M_n(\hat{h}) - M_{n-1}(\hat{h}))^2] &= \mathbb{E}_\pi[\{\hat{h}(X_1) - P\hat{h}(X_0)\}^2] \leq 2\mathbb{E}_\pi[\hat{h}^2(X_1) + (P\hat{h}(X_0))^2] \\ &= 2 \left[\pi(\hat{h}^2) + \pi((P\hat{h})^2) \right] \stackrel{(1)}{\leq} 2 \left[\pi(\hat{h}^2) + \underbrace{\pi P(\hat{h})^2}_\pi \right] = 2\pi(\hat{h}^2) < \infty \end{aligned}$$

where $\stackrel{(1)}{\leq}$ follows from Cauchy-Schwarz inequality. Therefore, the sequence $(M_n(\hat{h}))_{n \in \mathbb{N}}$ is a martingale with stationary and square integrable increments under \mathbb{P}_π . By Theorem 4.11, we have

$$n^{-1/2} M_n(\hat{h}) \xrightarrow{\mathcal{L}_{\mathbb{P}_\pi}^{\mathcal{L}_{\mathbb{P}_\pi}} \mathcal{N}\left(0, \mathbb{E}_\pi[\{\hat{h}(X_1) - P\hat{h}(X_0)\}^2]\right). \quad (4.17)$$

Since the Markov chain $(X_k)_{k \in \mathbb{N}}$ is stationary under \mathbb{P}_π , we get $\mathbb{E}_\pi[|\hat{h}(X_0) + \hat{h}(X_n)|] \leq 2\pi(|\hat{h}|)$ which implies that

$$n^{-1/2} \{\hat{h}(X_0) + \hat{h}(X_n)\} \xrightarrow{\mathbb{P}_\pi\text{-prob}} 0.$$

Combining it with (4.17) and (4.14) and using Slutsky's lemma gives:

$$n^{-1/2} \sum_{k=0}^{n-1} h(X_k) \xrightarrow{\mathcal{L}_{\mathbb{P}_\pi}^{\mathcal{L}_{\mathbb{P}_\pi}} \mathcal{N}(0, \sigma_\pi^2(h))$$

□

Theorem 4.13. *Assume that (A1) and (A2) hold for some function V . Then, for all measurable functions h such that $|h|^2 \leq V$,*

$$n^{-1/2} \sum_{k=0}^{n-1} h(X_k) \xrightarrow{\mathcal{L}_{\mathbb{P}_\pi}^{\mathcal{L}_{\mathbb{P}_\pi}} \mathcal{N}(0, \sigma_\pi^2(h)),$$

where

$$\sigma_\pi^2(h) = \mathbb{E}_\pi[\{\hat{h}(X_1) - P\hat{h}(X_0)\}^2] \quad (4.18)$$

and \hat{h} is defined as in (4.13).

Proof. Assume that (A1) and (A2) hold for some function V . Then, (A1) also holds with V replaced by $V^{1/2}$. Moreover, since $PV \leq \lambda V + b$, we have by Cauchy-Schwarz,

$$P(V^{1/2}) \leq (PV)^{1/2} \leq (\lambda V + b)^{1/2} \leq \lambda^{1/2} V^{1/2} + b^{1/2}$$

Finally, (A1) and (A2) hold for the function $V^{1/2}$. We can therefore apply Theorem 4.10 with V replaced by $V^{1/2}$. Then, for all $h \leq V^{1/2}$, the function \hat{h} defined by (4.13) is solution to the Poisson equation and there exists a constant $\gamma > 0$ such that $\hat{h} \leq \gamma V^{1/2}$. This implies that $\pi(\hat{h}^2) \leq \gamma\pi(V) < \infty$ by Theorem 4.7. Therefore $\hat{h} \in L_2(\pi)$ and Theorem 4.12 applies. The proof is completed. □

Under the assumptions of Theorem 4.13, the CLT holds under \mathbb{P}_π . We can actually extend this result to all \mathbb{P}_ν where ν is any probability measure in $\mathcal{M}_1(\mathbb{X})$.

4.4 After studying this chapter...

- a) I understand the three expressions of the total variation norm.
- b) If asked, I can try to prove that a Markov kernel is geometrically ergodic by checking the minorizing condition and the drift condition.
- c) I understand the coupling inequality.
- d) I understand the proof of Theorem 4.5, which is hard but also beautiful...
- e) I know what is a Poisson equation and I can write a solution of the Poisson equation as a series.
- f) I understand in what sense Poisson equation allows to establish links between Markov Chains and martingales.

Highlights

4.A Stanislaw Ulam (source: wikipedia).



Stanislaw Marcin Ulam (3 april 1909-13 may 1984) was a Polish-American scientist in the fields of mathematics and nuclear physics. He participated in the Manhattan Project, originated the Teller-Ulam design of thermonuclear weapons, discovered the concept of the cellular automaton, invented the Monte Carlo method of computation, and suggested nuclear pulse propulsion. In pure and applied mathematics, he proved some theorems and proposed several conjectures.

Born into a wealthy Polish Jewish family, Ulam studied mathematics at the Lwow Polytechnic Institute, where he earned his PhD in 1933 under the supervision of Kazimierz Kuratowski. In 1935, John von Neumann, whom Ulam had met in Warsaw, invited him to come to the Institute for Advanced Study in Princeton, New Jersey, for a few months. From 1936 to 1939, he spent summers in Poland and academic years at Harvard University in Cambridge, Massachusetts, where he worked to establish important results regarding ergodic theory. On 20 August 1939, he sailed for the United States for the last time with his 17-year-old brother Adam Ulam. He became an assistant professor at the University of Wisconsin-Madison in 1940, and a United States citizen in 1941.

In October 1943, he received an invitation from Hans Bethe to join the Manhattan Project at the secret Los Alamos Laboratory in New Mexico. There, he worked on the hydrodynamic calculations to predict the behavior of the explosive lenses that were needed by an implosion-type weapon. He was assigned to Edward Teller's group, where he worked on Teller's "Super" bomb for Teller and Enrico Fermi. After the war he left to become an associate professor at the University of Southern California, but returned to Los Alamos in 1946 to work on thermonuclear weapons. With the aid of a cadre of female "computers", including his wife Françoise Aron Ulam, he found that Teller's "Super" design was unworkable. In January 1951, Ulam and Teller came up with the Teller-Ulam design, which is the basis for all thermonuclear weapons.

Ulam considered the problem of nuclear propulsion of rockets, which was pursued by Project Rover, and proposed, as an alternative to Rover's nuclear thermal rocket, to harness small nuclear explosions for propulsion, which became Project Orion. With Fermi, John Pasta, and Mary Tsingou, Ulam studied the Fermi-Pasta-Ulam-Tsingou problem, which became the inspiration for the field of non-linear science. He is probably best known for realising that electronic computers made it practical to apply statistical methods to functions without known solutions, and as computers have developed, the Monte Carlo method has become a common and standard approach to many problems.

Chapter 5

Variants of MH algorithms

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Keywords: Pseudo-marginal algorithms, Hamiltonian Monte Carlo, leapfrog, Gibbs sampler.

In this chapter, we describe diverse variants of MH algorithms. Recall that we are given a target distribution π . In classical MH, we construct a Markov chain (X_k) that admits π as invariant probability measure. In most of the variants presented in this chapter, we extend (X_k) by adding a component, say (U_k) and such that (X_k, U_k) is a Markov chain that admits an invariant probability measure Π with the property that Π has π as its marginal distribution wrt the first component. Finally $(X_k)_{k \in \mathbb{N}}$ alone is not a Markov chain, on the contrary to $(X_k, U_k)_{k \in \mathbb{N}}$.

We start with a general version of MH algorithms that will be useful in many contexts.

5.1 Generalisation of MH Algorithms

Let $\pi \in \mathbf{M}_1(\mathbf{X})$ and let Q be a Markov kernel on $\mathbf{X} \times \mathcal{X}$. In Section 2.1.1, we have presented the Metropolis-Hastings algorithm when π and $Q(x, \cdot)$ have both densities wrt a common dominating measure λ . Here we do not make such an assumption so that the expression of α^{MH} given in Lemma 2.5 is not available anymore and should be adapted. Instead, we will need the following assumption. Define

$$\mu_0(dxdy) = \pi(dx)Q(x, dy) \quad \text{and} \quad \mu_1(dxdy) = \pi(dy)Q(y, dx).$$

(B1) There exists a function $(x, y) \mapsto r(x, y)$ such that $r(x, y) > 0$, μ_0 -a.s. and for all $h \in \mathbf{F}_+(\mathbf{X}^2)$,

$$\int h(x, y)\mu_1(dxdy) = \int h(x, y)r(x, y)\mu_0(dxdy) \tag{5.1}$$

This equation shows that the measure μ_1 is dominated by μ_0 with a μ_0 -a.s. positive density:

$$r(x, y) = \frac{d\mu_1}{d\mu_0}(x, y).$$

Then, by symmetry, we can easily show that $1/r(x, y) = r(y, x)$, μ_1 -a.s. And finally the two measures, μ_0 and μ_1 are equivalent (one is dominated by the other and conversely). In this case, the generalised version of the Metropolis-Hastings kernel, where α^{MH} given in Lemma 2.5 is replaced by $\alpha(x, y) = r(x, y) \wedge 1$ is π -reversible.

Lemma 5.1. *Assume (B1). Then, setting $\alpha(x, y) = r(x, y) \wedge 1$, the MH kernel:*

$$P_{\langle \pi, Q \rangle}^{MH}(x, dy) = Q(x, dy)\alpha(x, y) + \bar{\alpha}(x)\delta_x(dy) \quad \text{where} \quad \bar{\alpha}(x) = 1 - \int_{\mathbf{X}} Q(x, dy)\alpha(x, y)$$

is π -reversible.

Proof. Similarly to Lemma 2.4, we only need to check the detailed balance condition. Let $h \in \mathbf{F}_+(\mathbf{X})$, then,

$$\begin{aligned} \int_{\mathbf{X}^2} \pi(dx)Q(x, dy)\alpha(x, y)h(x, y) &= \int_{\mathbf{X}^2} \mu_0(dx dy)(r(x, y) \wedge 1)h(x, y) \\ &= \int_{\mathbf{X}^2} \mu_0(dx dy)r(x, y) \left(1 \wedge \frac{1}{r(x, y)}\right) h(x, y) = \int_{\mathbf{X}^2} \mu_1(dx dy) \left(1 \wedge \underbrace{1/r(x, y)}_{r(y, x)}\right) h(x, y) \\ &= \int_{\mathbf{X}^2} \pi(dy)Q(y, dx)\alpha(y, x)h(x, y). \end{aligned}$$

Thus, the detailed balance condition is verified and the proof is completed. \square

5.2 Pseudo marginal Monte Carlo methods

Assume that π and Q are dominated by a common dominating measure λ and write by abuse of notation, $\pi(dx) = \pi(x)\lambda(dx)$ and $Q(x, dy) = q(x, y)\lambda(dy)$. When considering a Metropolis-Hastings algorithm, we need an explicit expression of $\pi(x)$ for any $x \in \mathbf{X}$, up to a multiplicative constant. It may happen that we are not able to calculate $\pi(x)$ explicitly (even up to a multiplicative constant). Instead, assume that we are able to have an unbiased estimator of $\pi(x)$. To obtain such an unbiased estimator, say that you draw $W \sim R(x, dw)$ where R is a Markov kernel from \mathbf{X} to \mathbb{R}_*^+ , that is, a Markov kernel on $\mathbf{X} \times \mathcal{B}(\mathbb{R}_*^+)$ such that $\int_{\mathbb{R}_*^+} wR(x, dw) = \pi(x)$ (the *unbiasedness* condition).

The pseudo marginal algorithm works as described in Algorithm 2 below. Finally, this algorithm is very close to the classical MH except that we replace $\pi(x)$ by its unbiased estimator.

We now justify Pseudo-marginal Monte Carlo methods by showing that it is actually a ("disguised") generalized MH algorithm (as described in Lemma 5.1) by considering "extended Markov chain", $(\bar{X}_k)_{k \in \mathbb{N}} = (X_k, W_k)_{k \in \mathbb{N}}$ on an extended space and with an extended target. Define the extended target distribution $\bar{\Pi}(d\bar{x}) = \bar{\Pi}(dx dw) = wR(x, dw)\lambda(dx)$ (where we set $\bar{x} = (x, w)$). Note that $\bar{\Pi}$ is indeed a probability measure on $\bar{\mathbf{X}} = \mathbf{X} \times \mathbb{R}_*^+$, since

input : n
output: X_0, \dots, X_n
 At $t = 0$, draw X_0 according to some arbitrary distribution and draw $W_0 \sim R(X_0, \cdot)$
for $t \leftarrow 0$ **to** $n - 1$ **do**
 • Draw $\tilde{X}_{t+1} \sim Q(X_t, \cdot)$ and then $\tilde{W}_{t+1} \sim R(\tilde{X}_{t+1}, \cdot)$
 • Set $(X_{t+1}, W_{t+1}) = \begin{cases} (\tilde{X}_{t+1}, \tilde{W}_{t+1}) & \text{with prob. } \frac{\tilde{W}_{t+1} q(\tilde{X}_{t+1}, X_t)}{W_t q(X_t, \tilde{X}_{t+1})} \wedge 1 \\ (X_t, W_t) & \text{with prob. } 1 - \frac{\tilde{W}_{t+1} q(\tilde{X}_{t+1}, X_t)}{W_t q(X_t, \tilde{X}_{t+1})} \wedge 1 \end{cases}$
end

Algorithm 2: The Pseudo-Marginal MH Algorithm

$$\iint_{\mathbb{X} \times \mathbb{R}_+^+} \Pi(dx dw) = \int_{\mathbb{X}} \left(\int_{\mathbb{R}_+^+} w R(x, dw) \right) \lambda(dx) = \int_{\mathbb{X}} \pi(x) \lambda(dx) = 1$$

Moreover, in Algorithm 2, the candidate $(\tilde{X}_{t+1}, W_{t+1})$ is proposed according to \bar{Q} where the proposal kernel \bar{Q} is defined by $\bar{Q}(\bar{x}, d\bar{x}') = Q(x, dx') R(x', dw')$.

In order to check (B1), we first set

$$\begin{aligned} \mu_0(d\bar{x}d\bar{x}') &= \mu_0(dx dw dx' dw') = w R(x, dw) \lambda(dx) Q(x, dx') R(x', dw') \\ \mu_1(d\bar{x}d\bar{x}') &= \mu_1(dx dw dx' dw') = w' R(x', dw') \lambda(dx') Q(x', dx) R(x, dw). \end{aligned}$$

Then, writing $Q(x, dy) = q(x, y) \lambda(dy)$, we obtain for all $h \in F_+(\bar{\mathbb{X}}^2)$,

$$\begin{aligned} \int_{\bar{\mathbb{X}}^2} h(\bar{x}, \bar{x}') \mu_1(d\bar{x}d\bar{x}') &= \int_{\bar{\mathbb{X}}^2} h(\bar{x}, \bar{x}') w' q(x', x) [R(x, dw) R(x', dw') \lambda(dx) \lambda(dx')] \\ &= \int_{\bar{\mathbb{X}}^2} h(\bar{x}, \bar{x}') \underbrace{\frac{w' q(x', x)}{w q(x, x')}}_{r(\bar{x}, \bar{x}')} \mu_0(d\bar{x}d\bar{x}'). \end{aligned}$$

Since $r > 0$, we can apply Lemma 5.1 with $\alpha(\bar{x}, \bar{x}') = r(\bar{x}, \bar{x}') \wedge 1$ and we finally get that $P_{(\Pi, \bar{Q})}^{MH}(\bar{x}, d\bar{x}')$ is Π -reversible. Since Algorithm 2 corresponds to applying the Markov kernel $P_{(\Pi, \bar{Q})}^{MH}$, this completes the proof. Note that the extended target distribution Π has the marginal π wrt the first component:

$$\Pi(A \times \mathbb{R}_+^+) = \int_A \int_{\mathbb{R}_+^+} w R(x, dw) \lambda(dx) = \int_A \pi(dx) = \pi(A).$$

To sum up, $(\bar{X}_k)_{k \in \mathbb{N}} = (X_k, W_k)_{k \in \mathbb{N}}$ produced by Algorithm 2 is a generalized Metropolis-Hastings algorithm where the target distribution Π admits π as the marginal distribution on the first component. Note that $(X_k)_{k \in \mathbb{N}}$ is not a Markov chain anymore (but $(\bar{X}_k)_{k \in \mathbb{N}}$ is).

5.3 Hamiltonian Monte Carlo

In Hamiltonian Monte Carlo (HMC), we again extend the target density and construct a Markov chain on an extended space. We assume here that we have a target distribution on \mathbb{R}^d , say π , and we write $\pi(q) \propto e^{-U(q)}$ (in this literature, the "mute" variable x is replaced by q). Nothing very restrictive so far... We may consider π as the marginal of the extended target

$$\Pi(q, p) \propto \exp \{ -U(q) - p^T p / 2 \}, \quad p, q \in \mathbb{R}^d \quad (5.2)$$

We can see that this extended target density can be written as the product of two densities: π for the first component and the normal density of $\mathcal{N}(0, I_d)$ for the second component. At this stage, adding a second component in the target distribution that is completely independent of the first component and with such a classical distribution as $\mathcal{N}(0, I_d)$ does not seem to bring too much excitement in the problem but let's be patient... In what follows, we make use of the following terminology (that comes from physicists:)

- $q \in \mathbb{R}^d$ is the position and $U(q)$ is called the *potential energy*.
- $p \in \mathbb{R}^d$ is the momentum and $K(p) = p^T p / 2$ is called the *kinetic energy*.
- $H(q, p) = U(q) + K(p)$ is called the *Hamiltonian*.

Several versions of HMC exist. We consider in this course the Leapfrog HMC which produces a Markov chain $(X_t)_{t \in \mathbb{N}} = (q_t, p_t)_{t \in \mathbb{N}}$ as described in Algorithm 3:

```

input : n,h,L
output:  $X_0, \dots, X_n$ 
At  $t = 0$ , draw  $X_0$  according to some arbitrary distribution
for  $t \leftarrow 0$  to  $n - 1$  do
    • Set  $q_{t+1}^0 = q_t$  and draw  $p_{t+1}^0 \sim \mathcal{N}(0, I_d)$ 
    for  $k \leftarrow 0$  to  $L - 1$  do
         $p_{t+1}^{k+1/2} = p_{t+1}^k - (h/2)\nabla U(q_{t+1}^k)$ 
         $q_{t+1}^{k+1} = q_{t+1}^k - h p_{t+1}^{k+1/2}$ 
         $p_{t+1}^{k+1} = p_{t+1}^{k+1/2} - (h/2)\nabla U(q_{t+1}^{k+1})$ 
    end
    • With prob.  $\frac{\Pi(q_{t+1}^L, p_{t+1}^L)}{\Pi(q_{t+1}^0, p_{t+1}^0)} \wedge 1$ , set  $(q_{t+1}, p_{t+1}) = (q_{t+1}^L, p_{t+1}^L)$ .
    • Otherwise set  $(q_{t+1}, p_{t+1}) = (q_{t+1}^0, p_{t+1}^0)$ 
end

```

Algorithm 3: The Leapfrog HMC

A transition of this algorithm can be decomposed into two different (sub-)transitions:

- The first transition is $\begin{pmatrix} q_t \\ p_t \end{pmatrix} \rightarrow \begin{pmatrix} q_{t+1}^0 \\ p_{t+1}^0 \end{pmatrix}$ where one component is frozen $q_{t+1}^0 = q_t$, while the second one has been refreshed with $\mathcal{N}(0, I_d)$ which turns out to be also the conditional law $\Pi(dp|q)|_{q=q_t}$ (see (5.2)). A move where one component is fixed whereas the second one is according to the conditional distribution of the target is actually a Gibbs move and as a Gibbs move, the transition $\begin{pmatrix} q_t \\ p_t \end{pmatrix} \rightarrow \begin{pmatrix} q_{t+1}^0 \\ p_{t+1}^0 \end{pmatrix}$ is Π -reversible (please, check it carefully).
- The second transition concerns $\begin{pmatrix} q_{t+1}^0 \\ p_{t+1}^0 \end{pmatrix} \rightarrow \begin{pmatrix} q_{t+1} \\ p_{t+1} \end{pmatrix}$. It consists in (a) constructing a candidate $\begin{pmatrix} q_{t+1}^L \\ p_{t+1}^L \end{pmatrix}$ deterministically from $\begin{pmatrix} q_{t+1}^0 \\ p_{t+1}^0 \end{pmatrix}$ using L steps, and then (b) accept or refuse the proposed candidate according to some well-chosen probability. It looks like a **MH transition with deterministic moves** and we then have to check carefully that it is Π -reversible.

5.3.1 MH with deterministic moves

We start with a very simple question: can we construct a MH algorithm with target Π and where the proposal candidate is deterministic: $Q(x, dy) = \delta_{\varphi(x)}(dy)$? Of course due to the Dirac mass, we are not in a dominated framework but the question is: can we use a generalized MH algorithm as described in Section 5.1?

If yes, then we have to see if (B1) is satisfied. Set

$$\mu_0(\mathrm{d}x\mathrm{d}y) = \Pi(\mathrm{d}x)\delta_{\varphi(x)}(\mathrm{d}y) \quad \text{and} \quad \mu_1(\mathrm{d}x\mathrm{d}y) = \Pi(\mathrm{d}y)\delta_{\varphi(y)}(\mathrm{d}x),$$

and write for any non-negative function h ,

$$\begin{aligned} \int h(x, y)\mu_1(\mathrm{d}x\mathrm{d}y) &= \int \Pi(\mathrm{d}u)h(\underbrace{\varphi(u)}_v, \underbrace{u}_{\varphi^{-1}(v)}) \\ &= \int \Pi \circ \varphi^{-1}(\mathrm{d}v)h(v, \varphi^{-1}(v)) = \int \frac{\mathrm{d}\Pi \circ \varphi^{-1}}{\mathrm{d}\Pi}(v)\Pi(\mathrm{d}v)h(v, \varphi^{-1}(v)) \end{aligned}$$

Let us focus on the last term $\Pi(\mathrm{d}v)h(v, \varphi^{-1}(v))$. If we want to let appear the integral of $h(x, y)$ wrt to $\mu_0(\mathrm{d}x\mathrm{d}y) = \Pi(\mathrm{d}x)\delta_{\varphi(x)}(\mathrm{d}y)$, we need to assume that $\varphi^{-1}(v) = \varphi(v)$ that is φ is an **involution** and in such a case:

$$\int h(x, y)\mu_1(\mathrm{d}x\mathrm{d}y) = \int h(x, y)\frac{\mathrm{d}\Pi \circ \varphi^{-1}}{\mathrm{d}\Pi}(x)\mu_0(\mathrm{d}x\mathrm{d}y)$$

and the acceptance probability is then

$$\alpha(x, y) = \frac{\mathrm{d}\mu_1}{\mathrm{d}\mu_0}(x, y) \wedge 1 = \frac{\mathrm{d}\Pi \circ \varphi^{-1}}{\mathrm{d}\Pi}(x) \wedge 1$$

Remark 5.2. (i) A first point is that if we only use the involution, then after two steps we land up to the initial state... Not very interesting... Therefore, this deterministic transition is often combined with another move that is not deterministic. (In the Leapfrog, the first move is not deterministic: while we freeze the position, we refresh the momentum according to a Normal distribution).

(ii) For any involution, you can get a Metropolis Hastings with a theoretical expression of the acceptance probability as

$$\frac{\mathrm{d}\Pi \circ \varphi^{-1}}{\mathrm{d}\Pi}(x) \wedge 1$$

but the ideal HMC goes one step further since we can show that this is equal to 1. To get this, if we work on \mathbb{R}^d and if Π has density wrt the Lebesgue measure that we still denote Π , we get

$$\frac{\mathrm{d}\Pi \circ \varphi^{-1}}{\mathrm{d}\Pi}(x) = \frac{\Pi(\varphi^{-1}(x))}{\Pi(x)} \left| \frac{\partial \varphi^{-1}(x)}{\partial x} \right|$$

where the second term $\left| \frac{\partial \varphi^{-1}(x)}{\partial x} \right|$ is the Jacobian determinant of the mapping $\varphi^{-1} = \varphi$. To get 1 in the acceptance probability, we can impose that the two terms are equal to 1. The first term $\frac{\Pi(\varphi^{-1}(x))}{\Pi(x)}$ is one if the involution stays on **the same level set** (ie the moves according to φ does not change the value of Π) and the second term $\left| \frac{\partial \varphi^{-1}(x)}{\partial x} \right|$ is one if the involution is **volume-preserving**. If for example the involution only keeps the volume then the Radon Nikodym simplifies to

$$\frac{\Pi(\varphi^{-1}(x))}{\Pi(x)} = \frac{\Pi(\varphi(x))}{\Pi(x)} \quad \text{since} \quad \varphi \circ \varphi = \text{I}$$

To sum-up, MH with deterministic moves is possible but the mapping φ should be an involution. If the mapping should stay on the same level set and is volume preserving, the acceptance probability is even exactly equal to one.

5.3.2 Hamiltonian dynamics

5.3.2.1 Level sets

How can we find deterministic moves that stays on the same level set, ie, such that H and consequently, $H = U + K$ (the Hamiltonian) is constant.

If we now let (p, q) depend on a real parameter t and we impose to stay on a level set of H , we get:

$$\frac{dH(q^t, p^t)}{dt} = 0 = \sum_{i=1}^d \frac{\partial H(q^t, p^t)}{\partial q^{t,i}} \frac{dq^{t,i}}{dt} + \frac{\partial H(q^t, p^t)}{\partial p^{t,i}} \frac{dp^{t,i}}{dt}.$$

This gives the idea of using the following dynamics: for all $i \in [1 : d]$,

$$\begin{aligned} \frac{\partial H}{\partial q^{t,i}}(q^t, p^t) &= \frac{\partial U(q^t)}{\partial q^{t,i}} = -\frac{dp^{t,i}}{dt} \\ \frac{\partial H}{\partial p^{t,i}}(q^t, p^t) &= \frac{\partial K(p^t)}{\partial p^{t,i}} = p^{t,i} = \frac{dq^{t,i}}{dt} \quad \blacktriangleright \text{(Hamiltonian dynamics)} \end{aligned} \quad (5.3)$$

The very last equation leads to the interpretation of $p^{t,i}$ as a speed since it is the derivative of the position wrt time. Note $\phi^t(q, p) = (q^t, p^t)$ the (deterministic) position and momentum at time t when (q^s, p^s) follows the Hamiltonian dynamics (5.3). So, Hamiltonian dynamics moves along the **same level sets**. It can also be shown that it is **volume-preserving**. But unfortunately, it is not an involution. That's the bad news. But there is a also a good news: we can add a flip mapping on the second component after a move so that the resulting mapping is an involution. We will see it in the next paragraph.

5.3.2.2 The flip operator trick and the involution

Denote by $s(q, p) = (q, -p)$ the flip operator on the second component. The flip is also volume-preserving and moves along the level set so that finally, setting $f^T = s \circ \phi^T$, we obtain that f^T is volume-preserving and level-set invariant. We now show that f^T is an involution. Indeed, write $f^T(q, p) = (q^T, -p^T)$. To see what we obtain by applying again f^T , set $\tilde{q}^t = q^{T-t}$ and $\tilde{p}^t = -p^{T-t}$ so that $(\tilde{q}^0, \tilde{p}^0) = f^T(q, p)$. Then,

$$\begin{aligned} \frac{d\tilde{q}^{t,i}}{dt} &= \frac{dq^{T-t,i}}{dt} = -\left. \frac{dq^{s,i}}{ds} \right|_{s=T-t} = -p^{T-t,i} = \tilde{p}^{t,i} \\ \frac{d\tilde{p}^{t,i}}{dt} &= -\frac{dp^{T-t,i}}{dt} = -\left. \frac{dp^{s,i}}{ds} \right|_{s=T-t} = -\frac{\partial U(q^{T-t})}{\partial q^{T-t,i}} = -\frac{\partial U(\tilde{q}^{T-t})}{\partial \tilde{q}^{T-t,i}} \end{aligned}$$

Finally, the process $(\tilde{q}^t, \tilde{p}^t)$ follows the Hamiltonian dynamics so that $f^T(\tilde{q}^0, \tilde{p}^0) = (\tilde{q}^T, -\tilde{p}^T)$ and by definition this quantity is equal to (q^0, p^0) . We finally obtain that f^T is an involution.

The ideal HMC can be described as follows (Algorithm 4). We see in this ideal algorithm that the candidate is always accepted and that we don't even need to apply the flip operator (since it does not change at all the algorithm).

This is just an ideal algorithm since we don't know how to solve exactly Hamiltonian dynamics. The leapfrog is based on an approximation of these dynamics.


```

input : n, T
output:  $X_0, \dots, X_n$ 
At  $t = 0$ , draw  $X_0$  according to some arbitrary distribution
for  $t \leftarrow 0$  to  $n - 1$  do
  | • Set  $q_{t+1}^0 = q_t$  and draw  $p_{t+1}^0 \sim \mathcal{N}(0, I_d)$ 
  | • Set  $(q_{t+1}^L, p_{t+1}^L) = \phi^T(q_{t+1}^0, p_{t+1}^0)$ 
  | • Set  $(q_{t+1}, p_{t+1}) = (q_{t+1}^L, p_{t+1}^L)$ .
end

```

Algorithm 4: The ideal HMC.

5.3.3 The leapfrog integrator

5.3.3.1 Discretization and volume-preserving property

Recall that the Hamiltonian dynamics are: for all $i \in [1 : d]$,

$$\frac{\partial U(q^t)}{\partial q^{t,i}} = -\frac{dp^{t,i}}{dt}, \quad \text{and} \quad p^{t,i} = \frac{dq^{t,i}}{dt}$$

A first idea of discretization would be: choose a small stepsize h and a number of steps L and move according to: (for $k \in [1 : L]$),

$$\begin{aligned} p^{k+1} &= p^k - h\nabla U(q^k) \\ q^{k+1} &= q^k + hp^k \end{aligned}$$

Unfortunately, this discretization is associated to a mapping $(q_{k+1}, p_{k+1}) = \varphi(q_k, p_k)$ that is not volume-preserving... That is the absolute value of the Jacobian determinant of φ is not equal to one.

Instead, for any differentiable function ψ , the Jacobian matrix of a mapping where one component is frozen and the other one is updated by an additive term: $(x, y) \mapsto (x, y + \psi(x))$ is given by $\begin{pmatrix} 1 & 0 \\ \star & 1 \end{pmatrix}$ so that the determinant is one and this mapping is volume preserving...

Now, we will focus on the leapfrog discretization. Interested readers in other discretizations may try to solve Exercise 7.13 which focus on another discretization scheme.

The leapfrog discretization is defined by the following scheme: for $k \in [1 : L]$

$$\begin{aligned} p^{k+1/2} &= p^k - (h/2)\nabla U(q^k) \\ q^{k+1} &= q^k + hp^{k+1/2} \\ p^{k+1} &= p^{k+1/2} - (h/2)\nabla U(q^{k+1}) \end{aligned} \tag{5.4}$$

To see that it is volume-preserving, just note that a Leapfrog update can be decomposed into three mapping

$$(q^k, p^k) \xrightarrow{\varphi_1} (q^k, p^{k+1/2}) \xrightarrow{\varphi_2} (q^{k+1}, p^{k+1/2}) \xrightarrow{\varphi_1} (q^{k+1}, p^{k+1}). \tag{5.5}$$

where

$$\varphi_1(x, y) = (x, y - (h/2)\nabla U(x)) \quad \text{and} \quad \varphi_2(x, y) = (x + hy, y) \tag{5.6}$$

Each of these mappings keep one component frozen while the other component is updated with an additive term, so each of these mappings is volume-preserving and so is the Leapfrog update. To sum-up, the Leapfrog update is an approximation of the Hamiltonian dynamics, it is a deterministic mapping that is volume-preserving but not level-set invariant, so the acceptance probability will not be equal to 1, we still hope this is still high since it is an approximation of the Hamiltonian...

A very last property on the Leapfrog HMC should be checked (in order to say that the second step in Algorithm 3 is indeed a MH with deterministic moves): the involution property.

5.3.3.2 The flip operator trick and the involution property

To be specific, if we add the flip mapping s on the second component, then do we obtain an involution as for the ideal HMC?

Lemma 5.3. *For any $L \geq 1$, write $\Phi^{h,L}$ the Leapfrog mapping and define $f^{h,L} = s \circ \Phi^{h,L}$. Then $f^{h,L}$ is an involution.*

Proof. We will show that $f^{h,L} \circ f^{h,L} = Id$ by induction on L .

(i) We first show that $f^{h,1}$ is an involution.

Using (7.2), (5.5) and (5.6), we can check that

$$(q^k, p^k) \xrightarrow{\varphi_1} (q^k, p^{k+1/2}) \xrightarrow{\varphi_2} (q^{k+1}, p^{k+1/2}) \xrightarrow{\varphi_1} (q^{k+1}, p^{k+1}) \xrightarrow{s} (q^{k+1}, -p^{k+1}).$$

and

$$(q^{k+1}, -p^{k+1}) \xrightarrow{\varphi_1} (q^{k+1}, -p^{k+1/2}) \xrightarrow{\varphi_2} (q^k, -p^{k+1/2}) \xrightarrow{\varphi_1} (q^k, -p^k) \xrightarrow{s} (q^k, p^k).$$

Therefore: $f^{h,1} = s \circ \Phi^{h,1} = s \circ \varphi_1 \circ \varphi_2 \circ \varphi_1$ is an involution, i.e.

$$s \circ \Phi^{h,1} \circ s \circ \Phi^{h,1} = Id$$

Moreover, applying s on both sides of the equation and noting that s is an involution, we get $\Phi^{h,1} \circ s \circ \Phi^{h,1} = s$ (this will be useful two lines below).

(ii) Assume that for some $L \geq 1$, $f^{h,L}$ is an involution, that is $f^{h,L} \circ f^{h,L} = Id$. Now, write

$$f^{h,L+1} \circ f^{h,L+1} = s \circ \Phi^{h,L} \circ \underbrace{\Phi^{h,1} \circ s \circ \Phi^{h,1}}_s \circ \Phi^{h,L} = f^{h,L} \circ f^{h,L} = Id$$

by the induction assumption.

This completes the proof. □

5.4 Data augmentation

Throughout this section, (X, \mathcal{X}) and (Y, \mathcal{Y}) are Polish spaces equipped with their Borel σ -fields. Again, we wish to simulate from a probability measure π defined on (X, \mathcal{X}) using a sequence $\{X_k, k \in \mathbb{N}\}$ of X -valued random variables. Data augmentation algorithms consist in writing the target distribution π as the marginal of the distribution π^* on the product space $(X \times Y, \mathcal{X} \otimes \mathcal{Y})$ defined by $\pi^* = \pi \otimes R$ where R is a kernel on $X \times Y$. There exists also a kernel S on $Y \times X$ and a probability measure $\tilde{\pi}$ on (Y, \mathcal{Y}) such that $\pi^*(C) = \iint \mathbf{1}_C(x, y) \tilde{\pi}(dy) S(y, dx)$ for $C \in \mathcal{X} \otimes \mathcal{Y}$. In other words, if (X, Y) is a pair of random variables with distribution π^* , then $R(x, \cdot)$ is the distribution of Y conditionally on $X = x$ and $S(y, \cdot)$ is the distribution of X conditionally on $Y = y$. The bivariate distribution π^* can then be expressed as follows

$$\pi^*(dxdy) = \pi(dx)R(x, dy) = S(y, dx)\tilde{\pi}(dy). \quad (5.7)$$

A data augmentation algorithm consists in running a Markov Chain $\{(X_k, Y_k), k \in \mathbb{N}\}$ with invariant probability π^* and to use $n^{-1} \sum_{k=0}^{n-1} f(X_k)$ as an approximation of $\pi(f)$. A significant

difference between this general approach and a Metropolis-Hastings algorithm associated to the target distribution π is that $\{X_k, k \in \mathbb{N}\}$ is no longer constrained to be a Markov chain. The transition from (X_k, Y_k) to (X_{k+1}, Y_{k+1}) is decomposed into two successive steps: Y_{k+1} is first drawn given (X_k, Y_k) and then X_{k+1} is drawn given (X_k, Y_{k+1}) . Intuitively, Y_{k+1} can be used as an auxiliary variable, which directs the moves of X_k toward interesting regions with respect to the target distribution.

When sampling from R and S is feasible, a classical choice consists in following the two successive steps: given (X_k, Y_k) ,

- (i) sample Y_{k+1} from $R(X_k, \cdot)$,
- (ii) sample X_{k+1} from $S(Y_{k+1}, \cdot)$.

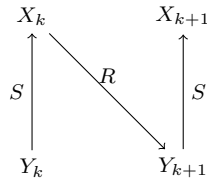


Fig. 5.1 In this example, sampling from R and S is feasible.

It turns out that $\{X_k, k \in \mathbb{N}\}$ is a Markov chain with Markov kernel RS and π is reversible wrt RS .

Lemma 5.4. *The distribution π is reversible with respect to the kernel RS .*

Proof. We must prove that the measure $\pi \otimes RS$ on \mathcal{X}^2 is symmetric. For $A, B \in \mathcal{X}$, applying (5.7), we have

$$\begin{aligned} \pi \otimes RS(A \times B) &= \int_{\mathcal{X} \times \mathcal{Y}} \pi(dx) R(x, dy) \mathbf{1}_A(x) S(y, B) = \int_{\mathcal{X} \times \mathcal{Y}} \mathbf{1}_A(x) S(y, B) \pi^*(dxdy) \\ &= \int_{\mathcal{X} \times \mathcal{Y}} \mathbf{1}_A(x) S(y, B) S(y, dx) \tilde{\pi}(dy) = \int_{\mathcal{Y}} S(y, A) S(y, B) \tilde{\pi}(dy). \end{aligned}$$

This proves that $\pi \otimes RS$ is symmetric. \square

Assume now that sampling from R or S is infeasible. In this case, we consider two instrumental kernels Q on $(\mathcal{X} \times \mathcal{Y}) \times \mathcal{Y}$ and T on $(\mathcal{X} \times \mathcal{Y}) \times \mathcal{X}$ which will be used to propose successive candidates for Y_{k+1} and X_{k+1} . For simplicity, assume that $R(x, dy')$ and $Q(x, y; dy')$ (resp. $S(y', dx')$ and $T(x, y'; dx')$) are dominated by the same measure and call r and q (resp. s and t) the associated transition densities. We assume that r and s are known up to a normalizing constant. Define the Markov chain $\{(X_k, Y_k), k \in \mathbb{N}\}$ as follows. Given $(X_k, Y_k) = (x, y)$,

- (DA1) draw a candidate \tilde{Y}_{k+1} according to the distribution $Q(x, y; \cdot)$ and accept $Y_{k+1} = \tilde{Y}_{k+1}$ with probability $\alpha(x, y, \tilde{Y}_{k+1})$ defined by

$$\alpha(x, y, y') = \frac{r(x, y')q(x, y'; y)}{r(x, y)q(x, y; y')} \wedge 1;$$

otherwise, set $Y_{k+1} = Y_k$; the Markov kernel on $\mathcal{X} \times \mathcal{Y} \times \mathcal{Y}$ associated to this transition is denoted by K_1 ;

(DA2) draw then a candidate \tilde{X}_{k+1} according to the distribution $T(x, Y_{k+1}; \cdot)$ and accept $X_{k+1} = \tilde{X}_{k+1}$ with probability $\beta(x, Y_{k+1}, \tilde{X}_{k+1})$ defined by

$$\beta(x, y, x') = \frac{s(y, x')t(x', y; x)}{s(y, x)t(x, y; x')} \wedge 1;$$

otherwise, set $X_{k+1} = X_k$; the Markov kernel on $\mathsf{X} \times \mathsf{Y} \times \mathcal{X}$ associated to this transition is denoted by K_2 .

For $i = 1, 2$, let K_i^* be the kernels associated to K_1 and K_2 as follows: for $x \in \mathsf{X}$, $y \in \mathsf{Y}$, $A \in \mathcal{X}$ and $B \in \mathcal{Y}$,

$$K_1^*(x, y; A \times B) = \mathbf{1}_A(x)K_1(x, y; B). \quad (5.8)$$

$$K_2^*(x, y; A \times B) = \mathbf{1}_B(y)K_2(x, y; A). \quad (5.9)$$

Then, the kernel of the chain $\{(X_n, Y_n), n \in \mathbb{N}\}$ is $K = K_1^*K_2^*$. The process $\{X_n, n \in \mathbb{N}\}$ is in general not a Markov chain since the distribution of X_{k+1} conditionally on (X_k, Y_k) depends on (X_k, Y_k) and on X_k only, except in some special cases. Obviously, this construction includes the previous one where sampling from R and S was feasible. Indeed, if $Q(x, y; \cdot) = R(x, \cdot)$ and $T(x, y; \cdot) = S(x, \cdot)$, then the acceptance probabilities α and β defined above simplify to one, the candidates are always accepted and we are back to the previous algorithm.

Proposition 5.5. *The extended target distribution π^* is reversible wrt the kernels K_1^* and K_2^* and invariant with respect to K .*

Proof. The reversibility of π^* with respect to K_1^* and K_2^* implies its invariance and consequently its invariance with respect to the product $K = K_1^*K_2^*$. Let us prove the reversibility of π^* with respect to K_1^* . For each $x \in \mathsf{X}$, the kernel $K_1(x, \cdot; \cdot)$ on $\mathsf{Y} \times \mathcal{Y}$ is the kernel of a Metropolis-Hastings algorithm with target density $r(x, \cdot)$, proposal kernel density $q(x, \cdot; \cdot)$ and acceptance probability $\alpha(x, \cdot, \cdot)$. It implies that the distribution $R(x, \cdot)$ is reversible with respect to the kernel $K_1(x, \cdot; \cdot)$. Applying the definition (5.8) of K_1^* and $\pi^* = \pi \otimes R$ yields, for $A, C \in \mathcal{X}$ and $B, D \in \mathcal{Y}$,

$$\begin{aligned} \pi^* \otimes K_1^*(A \times B \times C \times D) &= \iint_{A \times B} \pi(\mathrm{d}x \mathrm{d}y) K_1^*(x, y; C \times D) \\ &= \iint_{A \times B} \pi(\mathrm{d}x) R(x, \mathrm{d}y) \mathbf{1}_C(x) K_1(x, y, D) \\ &= \int_{A \cap C} \pi(\mathrm{d}x) [R(x, \cdot) \otimes K_1(x, \cdot; \cdot)](B \times D). \end{aligned}$$

We have seen that for each $x \in \mathsf{X}$, the measure $R(x, \cdot) \otimes K_1(x, \cdot; \cdot)$ is symmetric, thus $\pi^* \otimes K^*$ is also symmetric. The reversibility of π^* with respect to K_2^* is proved similarly. \square

Example 5.6 (The slice sampler). Set $\mathsf{X} = \mathbb{R}^d$ and $\mathcal{X} = \mathcal{B}(\mathsf{X})$. Let μ be a σ -finite measure on $(\mathsf{X}, \mathcal{X})$ and let h be the density with respect to μ of the target distribution. We assume that for all $x \in \mathsf{X}$,

$$h(x) = C \prod_{i=0}^k f_i(x),$$

where C is a constant (which is not necessarily known) and $f_i : \mathbb{R}^d \rightarrow \mathbb{R}^+$ are nonnegative measurable functions. For $y = (y_1, \dots, y_k) \in \mathbb{R}^{+k}$, define

$$L(y) = \{x \in \mathbb{R}^d : f_i(x) \geq y_i, i = 1, \dots, k\}.$$

The f_0 -slice-sampler algorithm proceeds as follows:

- given X_n , draw independently a k -tuple $Y_{n+1} = (Y_{n+1,1}, \dots, Y_{n+1,k})$ of independent random variables such that $Y_{n+1,i} \sim \text{Unif}(0, f_i(X_n))$, $i = 1, \dots, k$.
- sample X_{n+1} from the distribution with density proportional to $f_0 \mathbf{1}_{L(Y_{n+1})}$.

Set $\mathsf{Y} = (\mathbb{R}^+)^k$ and for $(x, y) \in \mathsf{X} \times \mathsf{Y}$,

$$h^*(x, y) = C f_0(x) \mathbf{1}_{L(y)}(x) = h(x) \prod_{i=1}^k \frac{\mathbf{1}_{[0, f_i(x)]}(y_i)}{f_i(x)}.$$

Let π^* be the probability measure with density h^* with respect to Lebesgue's measure on $\mathsf{X} \times \mathsf{Y}$. Then $\int_{\mathsf{Y}} h^*(x, y) dy = h(x)$ i.e. π is the first marginal of π^* . Let R be the kernel on $\mathsf{X} \times \mathsf{Y}$ with kernel density r defined by

$$r(x, y) = \frac{h^*(x, y)}{h(x)} \mathbf{1}_{h(x) > 0}.$$

Then $\pi^* = \pi \otimes R$. Define the distribution $\tilde{\pi} = \pi R$, its density $\tilde{h}(y) = \int_{\mathsf{X}} h^*(u, y) du$ and the kernel S on $\mathsf{Y} \times \mathsf{X}$ with density s by

$$s(y, x) = \frac{h^*(x, y)}{\tilde{h}(y)} \mathbf{1}_{\tilde{h}(y) > 0}.$$

If (X, Y) is a vector with distribution π^* , then $S(y, \cdot)$ is the conditional distribution of X given $Y = y$ and the Markov kernel of the chain $\{X_n, n \in \mathbb{N}\}$ is RS and Lemma 5.4 can be applied to prove that π is reversible, hence invariant, with respect to RS .

5.4.1 Two-stage Gibbs sampler

The Gibbs sampler is a simple method which decomposes a complex multidimensional distribution into a collection of smaller dimensional ones. Let $(\mathsf{X}, \mathcal{X})$ and $(\mathsf{Y}, \mathcal{Y})$ be complete separable metric spaces endowed with their Borel σ -fields. To construct the Markov chain $\{(X_n, Y_n), n \in \mathbb{N}\}$ with π^* as an invariant probability, we proceed exactly as in data-augmentation algorithms. Assume that π^* may be written as

$$\pi^*(dx dy) = \pi(dx) R(x, dy) = \tilde{\pi}(dy) S(y, dx) \tag{5.10}$$

where π and $\tilde{\pi}$ are probability measures on X and Y respectively and R and S are kernels on $\mathsf{X} \times \mathsf{Y}$ and $\mathsf{Y} \times \mathsf{X}$ respectively.

The deterministic updating (two-stage) Gibbs (DUGS) sampler

When sampling from R and S is feasible, the DUGS sampler proceeds as follows: given (X_k, Y_k) ,

- (DUGS1) sample Y_{k+1} from $R(X_k, \cdot)$,
- (DUGS2) sample X_{k+1} from $S(Y_{k+1}, \cdot)$.

For both the Data Augmentation algorithms and the two-stage Gibbs sampler we consider a distribution π^* on the product space $\mathsf{X} \times \mathsf{Y}$. In the former case, the distribution of interest is a marginal distribution of π^* and in the latter case the target distribution is π^* itself.

We may associate to each update (DUGS1)-(DUGS2) of the algorithm a transition kernel on $(\mathsf{X} \times \mathsf{Y}) \times (\mathcal{X} \otimes \mathcal{Y})$ defined for $(x, y) \in \mathsf{X} \times \mathsf{Y}$ and $A \times B \in \mathcal{X} \otimes \mathcal{Y}$ by

$$R^*(x, y; A \times B) = \mathbf{1}_A(x)R(x, B), \quad (5.11)$$

$$S^*(x, y; A \times B) = \mathbf{1}_B(y)S(y, A). \quad (5.12)$$

The transition kernel of the DUGS is then given by

$$P_{\text{DUGS}} = R^* S^*. \quad (5.13)$$

Note that for $A \times B \in \mathcal{X} \otimes \mathcal{Y}$,

$$\begin{aligned} P_{\text{DUGS}}(x, y; A \times B) &= \iint_{\mathsf{X} \times \mathsf{Y}} R^*(x, y; dx' dy') S^*(x', y'; A \times B) \\ &= \iint_{\mathsf{X} \times \mathsf{Y}} R(x, dy') \mathbf{1}_B(y') S(y', A) \\ &= \int_B R(x, dy') S(y', A) = R \otimes S(x, B \times A). \end{aligned} \quad (5.14)$$

As a consequence of Proposition 5.5, we obtain the invariance of π^* .

Lemma 5.7. *The distribution π^* is reversible with respect to the kernels R^* and S^* and invariant with respect to P_{DUGS} .*

The Random Scan Gibbs sampler (RSGS)

At each iteration, the RSGS algorithm consists in updating one component chosen at random. It proceeds as follows: given (X_k, Y_k) ,

- (RSGS1) sample a Bernoulli random variable B_{k+1} with probability of success $1/2$.
- (RSGS2) If $B_{k+1} = 0$, then sample Y_{k+1} from $R(X_k, \cdot)$ else sample X_{k+1} from $S(Y_{k+1}, \cdot)$.

The transition kernel of the RSGS algorithm can be written

$$P_{\text{RSGS}} = \frac{1}{2}R^* + \frac{1}{2}S^*. \quad (5.15)$$

Lemma 5.7 implies that P_{RSGS} is reversible wrt π^* and therefore π^* is invariant for P_{RSGS} .

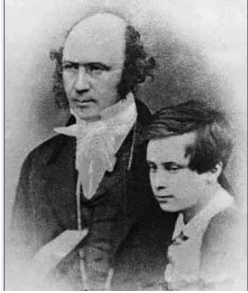
If sampling from R or S is infeasible, the Gibbs transitions can be replaced by a Metropolis-Hastings algorithm on each component as in the case of the DUGS algorithm. The algorithm is then called the Two-Stage Metropolis-within-Gibbs algorithm.

5.5 After studying this chapter...

- a) I can explain Pseudo marginal algorithm and I can justify why it is correct on a blackboard.
- b) I understand understand the notions of deterministic moves and the requirements linked with MH with deterministic moves (involution, volume-preserving and invariant level sets), so I understand all about Hamiltonian MC.
- c) I know and understand the Gibbs moves.
- d) I am able to implement these variants of MH, pseudo marginal algorithms, Leapfrog HMC...

Highlights

5.A William Rowan Hamilton (source: wikipedia).



Sir William Rowan Hamilton MRIA (3 August 1805 - 2 September 1865) was an Irish mathematician, Andrews Professor of Astronomy at Trinity College Dublin, and Royal Astronomer of Ireland. He worked in both pure mathematics and mathematics for physics. He made important contributions to optics, classical mechanics and algebra. Although Hamilton was not a physicist, he regarded himself as a pure mathematician, his work was of major importance to physics, particularly his reformulation of Newtonian mechanics, now called Hamiltonian mechanics. This work has proven central to the modern study of classical field theories such as electromagnetism, and to the development of quantum mechanics. In pure mathematics, he is best known as the inventor of quaternions.

William Rowan Hamilton's scientific career included the study of geometrical optics, classical mechanics, adaptation of dynamic methods in optical systems, applying quaternion and vector methods to problems in mechanics and in geometry, development of theories of conjugate algebraic couple functions (in which complex numbers are constructed as ordered pairs of real numbers), solvability of polynomial equations and general quintic polynomial solvable by radicals, the analysis on Fluctuating Functions (and the ideas from Fourier analysis), linear operators on quaternions and proving a result for linear operators on the space of quaternions (which is a special case of the general theorem which today is known as the Cayley-Hamilton theorem). Hamilton also invented "icosian calculus", which he used to investigate closed edge paths on a dodecahedron that visit each vertex exactly once.

Chapter 6

Target distributions and alternative methods

So far, in MCMC methods, a target distribution π is given and we have shown some generic ways of constructing a process $(X_k)_{k \in \mathbb{N}}$ that targets π in some sense to be defined: sometimes $(X_k)_{k \in \mathbb{N}}$ is itself a Markov chain with invariant probability measure π , sometimes, $(X_k)_{k \in \mathbb{N}}$ is the first component process of an extended Markov chain that targets an extended distribution where the marginal distribution on the first component is π .

6.1 Target distributions

We first introduce two contexts where target distributions are at stake. One is linked with Bayesian inference. In such a case, the target distribution is the posterior distribution of the parameter given all the data. Another one is linked with partially observed models. In such a case, the target distribution might be the distribution of the unobserved variables given the data.

6.1.1 Bayesian inference

In Bayesian inference, prior belief is combined with data to obtain posterior distributions on which statistical inference is based. Except for some simple cases, Bayesian inference can be computationally intensive and may rely on computational techniques.

The basic idea in Bayesian analysis is that a parameter vector, say $\theta \in \Theta$, is unknown to a researcher, so a *prior* distribution, $\pi_0(\theta)\lambda(d\theta)$, is put on the parameter vector. The researcher also proposes a model or likelihood, $p(y_{1:n} | \theta)$, that describes how the data $Y = y_{1:n}$ depend on the parameter vector. Inference about θ is then based on the *posterior* distribution, which is obtained via Bayes's theorem,

$$\pi(\theta) = p(\theta | Y = y_{1:n}) = \frac{\pi_0(\theta) p(y_{1:n} | \theta)}{\int \pi_0(\theta) p(y_{1:n} | \theta) \lambda(d\theta)}. \quad (6.1)$$

In some simple cases, the prior and the likelihood are *conjugate* distributions that may be combined easily. For example, in n fixed repeated (iid) Bernoulli experiments with probability of success θ , a *Beta-Binomial* conjugate pair is taken. In this case the prior is $\text{Beta}(a, b)$: $\pi_0(\theta) \propto \theta^a (1 - \theta)^b$; the values $a, b > -1$ are called hyperparameters. The likelihood in this example is $\text{Binomial}(n, \theta)$:

$p(y | \theta) \propto \theta^y (1 - \theta)^{n-y}$, from which we easily deduce that the posterior is also Beta, $\pi(\theta | Y) \propto \theta^{y+a} (1 - \theta)^{n+b-y}$, and from which inference may easily be achieved. In more complex experiments, the posterior distribution is often difficult to obtain by direct calculation, so MCMC techniques are employed (note that in (6.1), the numerator is usually known and explicit while, due to the integral, the denominator is a multiplicative unknown constant). The main idea is that we may not be able to explicitly display the posterior, but we may be able to simulate from the posterior.

6.1.2 Models with Latent variables

In some situations, observations are partial and unfortunately, do not contain some variables of interest. In such a case, given a modelization of the process generating the data, one might be interested into reconstructing the distribution of the missing variables given the data. This will be our target distribution. Let us be more specific with the example of Hidden Markov Models (HMM).

Such a model is defined by a bivariate Markov chain $(Z_k)_{k \in \mathbb{N}} = (X_k, Y_k)_{k \in \mathbb{N}}$ on $\mathsf{X} \times \mathsf{Y}$ where $(\mathsf{X}, \mathcal{X})$ and $(\mathsf{Y}, \mathcal{Y})$ are two measurable spaces, and where the transition is given by:

$$\begin{aligned} X_k | Z_{0:k-1} &\sim Q(X_{k-1}, \cdot) \\ Y_k | X_k, Z_{0:k-1} &\sim G(X_k, \cdot) \end{aligned}$$

Here, Q denotes a Markov kernel on $\mathsf{X} \times \mathcal{X}$ while G is a Markov kernel on $\mathsf{X} \times \mathcal{Y}$.

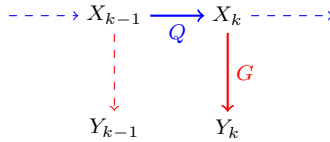


Fig. 6.1 A hidden Markov model

In such a model, only the Y 's component is observed and inference must be driven on the basis of $(Y_{1:n})$ only. In a fully dominated model, we assume that $Q(x, dx') = q(x, x')\lambda(dx')$ and $G(x, dy) = g(x, y)\nu(dy)$ where λ and ν are σ -finite dominating measures on $(\mathsf{X}, \mathcal{X})$, and $(\mathsf{Y}, \mathcal{Y})$ respectively. In such a case, assuming that $X_0 = x_0$ is given, one might be interested in the law of the missing variables $X_{1:n}$ given the observations $Y_{1:n}$, so that the target density will be:

$$\pi(x_{1:n}) = \frac{\prod_{i=1}^n q(x_{i-1}, x_i) g(x_i, y_i)}{\int \cdots \int_{\mathsf{X}^n} \prod_{i=1}^n q(x_{i-1}, x_i) g(x_i, y_i) \lambda(dx_i)}$$

Once again the denominator is, due to the integral, an unknown multiplicative factor, whereas the numerator is explicit and we are therefore in a context where MCMC methods can be applied. Nevertheless, in this example, the number of hidden variables is n , which can be very large and the target distribution is thus associated to a very high dimensional space, X^n , so that we have to be very careful when applying these methods.

6.2 Other approximation methods

In computational statistics, when it comes to approaching a target law in a very large space, classical techniques using Markov chains admitting "exactly" this target law for invariant distribution may suffer from a slow exploration of the state space. In a high dimensional framework, the candidate is often proposed in an uninformative region and it is likely that it is refused, leading the Markov chain to remain stuck at the same place a certain amount of time.

Some other approximation techniques do not even try to construct random variables with distribution close to π . We will briefly introduce two approximation techniques: sequential Monte Carlo methods and Variational Inference.

6.2.1 Sequential Monte Carlo methods

We briefly explain basic ideas of Sequential Monte Carlo methods, without proving anything. The rough idea of sequential Monte Carlo methods for targetting π is to find intermediate target distributions $\pi_1 \rightarrow \pi_2 \rightarrow \dots \rightarrow \pi_T = \pi$ and to construct, sequentially, Monte Carlo approximations of π_i .

This is actually based on importance sampling and we first recall it here. If π and g are densities wrt to the same dominating measure, and assuming that $g(x) = 0$ implies $\pi(x) = 0$, then we can approximate $\pi(h)$ with $N^{-1} \sum_{k=1}^N \frac{\pi(X_k)}{g(X_k)} h(X_k)$ where $(X_k)_{k \in [1:N]} \stackrel{\text{i.i.d.}}{\sim} g$. Since π is typically known only up to a multiplicative factor, the quantity $n^{-1} \sum_{k=1}^N \frac{\pi(X_k)}{g(X_k)} h(X_k)$ is not explicit due to this multiplicative factor and we typically choose instead:

$$\pi(h) = \frac{\pi(h)}{\pi(1)} \approx \frac{n^{-1} \sum_{k=1}^N \frac{\pi(X_k)}{g(X_k)} h(X_k)}{N^{-1} \sum_{\ell=1}^N \frac{\pi(X_\ell)}{g(X_\ell)}} = \sum_{k=1}^N \left(\frac{\omega^k}{\sum_{\ell=1}^N \omega^\ell} \right) h(X_k) = \sum_{k=1}^N \bar{\omega}^k h(X_k)$$

where $\omega^k = \pi(X_k)/g(X_k)$ and $\bar{\omega}^k = \omega^k / (\sum_{\ell=1}^k \omega^\ell)$. Now the rhs can be calculated even if π is known only up to a multiplicative factor since $\bar{\omega}^k$ is a ratio where π is involved (both in the numerator and the denominator).

Thus, $\pi(h)$ is approximated using a population of "particles" $\{(X_k, \omega^k)\}_{k \in [1:N]}$ (we mean by particle a "support" point X_k and an associated weight ω^k). Note that a weight is usually unnormalized but when considering the approximation, we use the normalized weights: $\omega^k / (\sum_{\ell=1}^k \omega^\ell)$.

Of course, if all the X_k were iid from π directly, all the associated weights would be equal. So here, by allowing different weights, we are more flexible. Still if the weights are too different, this is not satisfactory because only a few particles contain all the information. In that case, we prefer to resample inside the population. Let us be more specific.

6.2.1.1 Resampling step

Assume that $\{(X_k, \omega^k)\}_{k \in [1:N]}$ targets $\pi_0(h)$. Define $\bar{\omega}^k = \omega^k / (\sum_{\ell=1}^k \omega^\ell)$.

An example of resampling step is

$$\text{For } k \in [1 : n], \text{ choose independently } \tilde{X}_k = \begin{cases} X_1 & \text{wp } \bar{\omega}^1 \\ \dots & \\ X_N & \text{wp } \bar{\omega}^N \end{cases}$$

Then $\{(\tilde{X}_k, 1)\}_{k \in [1:N]}$ still targets $\pi_0(h)$. The target distribution is not changed but now, all the weights are equal. Informative particles (ie with high weights) are likely to be replicated after

resampling while noninformative are likely to disappear (because they were not chosen). Support points are changed but still within the initial pool of support points.

6.2.1.2 Exploration step

Assume that $\{(X_k, \omega^k)\}_{k \in [1:N]}$ targets $\pi_0(h)$ and that

$$\pi_1(y) = \int_{\mathcal{X}} \pi_0(dx) q(x, y), \quad (6.2)$$

where q is a kernel density. An example of exploration step is

$$\text{For } k \in [1 : n], \text{ draw independently } \tilde{X}_k \sim r(X_k, \cdot)$$

where r is a kernel density (that can be easily simulated). Then, $\left\{(\tilde{X}_k, \omega^k \times \frac{q(X_k, \tilde{X}_k)}{r(X_k, \tilde{X}_k)})\right\}_{k \in [1:N]}$ targets $\pi_1(h)$. Here, support points are moved and weights are updated by a multiplicative factor (except when $r = q$, in which case, support points are moved but the associated weights do not need to be updated since $\frac{q(X_k, \tilde{X}_k)}{r(X_k, \tilde{X}_k)} = 1$).

6.2.1.3 Reweighting step

Assume that $\{(X_k, \omega^k)\}_{k \in [1:N]}$ targets $\pi_0(h)$ and that

$$\pi_1(x) = \frac{\pi_0(x)g(x)}{\int_{\mathcal{X}} \pi_0(du)g(u)} \quad (6.3)$$

where g is a nonnegative function. Then, $\{(X_k, \omega^k g(X_k))\}_{k \in [1:N]}$ targets $\pi_1(h)$. Here, support points are unchanged but weights are updated.

Finally, when choosing the intermediate target distributions $\pi_1 \rightarrow \pi_2 \rightarrow \dots \rightarrow \pi_T = \pi$, we must check that each step $\pi_i \rightarrow \pi_{i+1}$ corresponds either to (6.2) or (6.3) so that we can let evolve a population of particles through exploration, and reweighting steps. Resampling can always be performed when weights are too different and this is often measured when the Effective Sample Size (which is a real number between 1 and N), $\widehat{ESS} = \frac{1}{\sum_{k=1}^N (\bar{\omega}^k)^2}$, falls below a certain arbitrary threshold.

6.2.2 Variational inference

Variational Inference is a technique derived from the *Machine Learning* community whose principle is to approach the target density through various optimization techniques. The principle consists in giving up aiming exactly at the target law, but instead, we have at hand a sufficiently rich family of laws (that can be easily simulated) and the idea is then to select a member of this family close to the target in the sense of a certain divergence through optimization procedures. Variational inference has been successfully used in many applications and seems to be faster and more efficient to explore large spaces compared to classical Monte Carlo Markov chain methods. The proximity is often measured in terms of Kullback divergence or even more recently in terms of f -divergence. Although these techniques are extremely powerful and popular in practice, some statistical properties of these methods are still largely unknown.

6.2.2.1 α -divergence and the ELBO

Letting f_α be the convex function on $(0, +\infty)$ defined by $f_0(u) = -\log(u)$, $f_1(u) = u \log(u)$ and $f_\alpha(u) = \frac{1}{\alpha(\alpha-1)} [u^\alpha - 1]$ for all $\alpha \in \mathbb{R} \setminus \{0, 1\}$, the α -divergence for all $\alpha \in \mathbb{R}$ is defined by

$$D_\alpha(\mathbb{P} \parallel \mathbb{Q}) = \int_{\mathcal{X}} f_\alpha \left(\frac{q(x)}{p(x)} \right) p(x) \lambda(dx), \quad (6.4)$$

where $\mathbb{P}(dx) = p(x) \lambda(dx)$ and $\mathbb{Q}(dx) = q(x) \lambda(dx)$. Of course, it is non-negative and null if $\mathbb{P} = \mathbb{Q}$ but there is no triangular inequality and therefore, it is not a distance.

In Variational Inference (also called VI), we want to approximate π by selecting the best candidate among a family of densities

$$\{x \mapsto p_\theta(x) : \theta \in \Theta\}$$

with respect to the α -divergence. In other words, we want to solve

$$\operatorname{argmin}_{\theta \in \Theta} D_\alpha(\pi \parallel p_\theta) = \operatorname{argmin}_{\theta \in \Theta} \int_{\mathcal{X}} f_\alpha \left(\frac{p_\theta(x)}{\pi(x)} \right) \pi(x) \lambda(dx)$$

Recalling that π is known only up to multiplicative constant, we must check if the minimization of $\int_{\mathcal{X}} f_\alpha \left(\frac{p_\theta(x)}{\pi(x)} \right) \pi(x) \lambda(dx)$ can be equivalent to the minimization of another functional which will be more explicit. Write $\pi(x) = \tilde{\pi}(x)/C$ where $\tilde{\pi}(x)$ is explicit and $C = \int_{\mathcal{X}} \tilde{\pi}(x) \lambda(dx)$ is an "unexplicit" constant. Take for example: $\alpha = 1$. Then,

$$D_1(\pi \parallel p_\theta) = \int_{\mathcal{X}} \log \left(\frac{p_\theta(x)}{\pi(x)} \right) p_\theta(x) \lambda(dx) = - \underbrace{\int_{\mathcal{X}} \log \left(\frac{\tilde{\pi}(x)}{p_\theta(x)} \right) p_\theta(x) \lambda(dx)}_{ELBO} + \log C$$

In this litterature, $\int_{\mathcal{X}} \log \left(\frac{\tilde{\pi}(x)}{p_\theta(x)} \right) p_\theta(x) \lambda(dx)$ is called the ELBO (Evidence Lower Bound) and maximizing the ELBO wrt θ is equivalent to minimizing $D_1(\pi \parallel p_\theta)$ wrt θ . Note that since $D_1(\pi \parallel p_\theta) = -ELBO + \log C$, we have

$$ELBO \leq \log C = \log \int_{\mathcal{X}} \tilde{\pi}(x) \lambda(dx)$$

(Hence, the terminology "Evidence Lower Bound"). In the case where $\alpha \neq 1$, some equivalent of the ELBO can also be found. In VI, we are face to an optimisation problem (which is in general a non-convex problem) and we have to resort to all the tools linked with optimisation problems: various stochastic gradient descents and their variants...

6.3 Approximate Bayesian computation

Approximate Bayesian computation (ABC) is an alternative approach when computation of the posterior is challenging, either because the size of the data or the complexity of realistic models makes the calculation computationally intractable. ABC specifically provides a solution when the likelihood $y \mapsto p(y|\theta)$ cannot be evaluated. A generic description of the original ABC algorithm requires (i) the introduction of statistics $S(y) \in \mathbb{R}^m$ where m is usually sensibly smaller than the dimension of y and (ii) a distance d on $\mathbb{R}^m \times \mathbb{R}^m$. Note that if no statistics can be widely defined S can be the identity function. Then, the most direct ABC algorithm is described in Algorithm 5.

Data: Observation Y , threshold ε , N
Result: Samples approximately distributed according to $p(\cdot|Y)$.
for $i = 1 \rightarrow N$ **do**
 | draw θ_i with prior distribution π ;
 | draw Y_i with distribution $p(\cdot|\theta_i)$;
end
Return all θ_i such that $d(S(Y_i), S(Y)) < \varepsilon$;

Algorithm 5: ABC algorithm.

When S is the identity function, the random variables sampled by this algorithm have distribution $\pi_\varepsilon(\cdot|Y)$ where

$$\pi_\varepsilon(\theta|Y) \propto \int p(y|\theta)\pi(\theta)\mathbb{1}_{A_{\varepsilon,Y}}(y)dy,$$

with $A_{\varepsilon,Y} = \{y; d(y, Y) < \varepsilon\}$. The intuitive idea behind this algorithm is that if $\varepsilon \rightarrow 0$, $\pi_\varepsilon(\theta|Y) \rightarrow \pi(\theta|Y)$ and if $\varepsilon \rightarrow \infty$, $\pi_\varepsilon(\theta|Y) \rightarrow \pi(\theta)$. This initial version of the ABC approach raises many practical issues among which an appropriate calibration of ε , the choice of statistics S , and the widespread inefficiency of sampling candidates according to the prior distribution π . In practice, the threshold ε is usually determined as a quantile of the observed distance $(d(S(Y_i), S(Y)))_{1 \leq i \leq N}$ which allows to introduce Algorithm 6.

Data: Observation Y , N , integer M_N
Result: Samples approximately distributed according to $p(\cdot|Y)$.
for $i = 1 \rightarrow N$ **do**
 | draw θ_i with prior distribution π ;
 | draw Y_i with distribution $p(\cdot|\theta_i)$;
end
Return all θ_i such that $S(Y_i)$ is in the set of M_N nearest neighbors of $S(Y)$ with respect to distance d ;

Algorithm 6: ABC algorithm with calibrated threshold.

These two algorithms generate independent samples but do not build upon the accepted samples to propose new candidates in a more efficient way than using the prior distribution. This can be performed by considering ABC within a MCMC algorithm. See the exercises for a proof that Algorithm 7 targets the correct posterior distribution.

Data: Observation Y , N , threshold ε , output (θ_0, Y_0) from a "standard" ABC.
Result: Samples approximately distributed according to $p(\cdot|Y)$.
for $i = 1$ *to* N **do**
 | Sample $\tilde{\theta} \sim q(\cdot|\theta_i)$;
 | Sample $\tilde{Y} \sim p(\cdot|\tilde{\theta})$ and compute $S(\tilde{Y})$;
 | Compute $\alpha = 1 \wedge \frac{\pi(\tilde{\theta})q(\theta_i|\tilde{\theta})}{\pi(\theta_i)q(\tilde{\theta}|\theta_i)} \mathbb{1}_{d(S(\tilde{Y}), S(Y)) < \varepsilon}$;
 | Sample $U \sim U(0, 1)$;
 | **if** $U < \alpha$ **then**
 | Set $\theta_{i+1} = \tilde{\theta}$ and $Y_{i+1} = \tilde{Y}$;
 | **else**
 | $\theta_{i+1} = \theta_i$ and $Y_{i+1} = Y_i$;
 | **end**
end

Algorithm 7: ABC within MCMC

6.4 After studying this chapter...

- a) I understand what are the typical target distributions and that they can be of high dimensions.
- b) I have notions other approximations methods.
- c) I understand the basic ways of letting evolve a population of particles (exploration, reweighting, resampling) and the associated moves of the target distribution.
- d) I understand the basics of variational inference.
- e) I am ready (and eager) to work in practise on various MH algorithms or approximation methods.

Highlights

6.A Thomas Bayes (source: wikipedia).



Thomas Bayes (1701-1761) was an English statistician, philosopher and Presbyterian minister who is known for formulating a specific case of the theorem that bears his name: Bayes' theorem. Bayes never published what would become his most famous accomplishment; his notes were edited and published after his death by Richard Price.

Thomas Bayes was the son of London Presbyterian minister Joshua Bayes, and was possibly born in Hertfordshire. He came from a prominent nonconformist family from Sheffield. In 1719, he enrolled at the University of Edinburgh to study logic and theology. On his return around 1722, he assisted his father at the latter's chapel in London before moving to Tunbridge Wells, Kent, around 1734. There he was minister of the Mount Sion Chapel, until 1752.

He is known to have published two works in his lifetime, one theological and one mathematical:

- Divine Benevolence, or an Attempt to Prove That the Principal End of the Divine Providence and Government is the Happiness of His Creatures (1731)
- An Introduction to the Doctrine of Fluxions, and a Defence of the Mathematicians Against the Objections of the Author of The Analyst (published anonymously in 1736), in which he defended the logical foundation of Isaac Newton's calculus ("fluxions") against the criticism of George Berkeley, author of The Analyst

It is speculated that Bayes was elected as a Fellow of the Royal Society in 1742 on the strength of the Introduction to the Doctrine of Fluxions, as he is not known to have published any other mathematical works during his lifetime.

In his later years he took a deep interest in probability. Professor Stephen Stigler, historian of statistical science, thinks that Bayes became interested in the subject while reviewing a work written in 1755 by Thomas Simpson, but George Alfred Barnard thinks he learned mathematics and probability from a book by Abraham de Moivre. Others speculate he was motivated to rebut David Hume's argument against believing in miracles on the evidence of testimony in An Enquiry Concerning Human Understanding. His work and findings on probability theory were passed in manuscript form to his friend Richard Price after his death.

Monument to members of the Bayes and Cotton families, including Thomas Bayes and his father Joshua, in Bunhill Fields burial ground By 1755 he was ill and by 1761 had died in Tunbridge Wells. He was buried in Bunhill Fields burial ground in Moorgate, London, where many nonconformists lie.

Illustrations, exercises, extensions

7.1 Illustrations

A “collaboratory” **Jupyter Notebook** that illustrates the results of some exercises or some algorithms seen in the course is at the disposal of the reader by following this link.

7.1.1 Illustrations of HMC

Figure 7.1.1 displays several trajectories of the leapfrog integrator when the target density is a Gaussian distribution or a mixture of Gaussian distributions. Trajectories are initialized randomly and then the leapfrog integrator is run with step size $h = 0.01$.

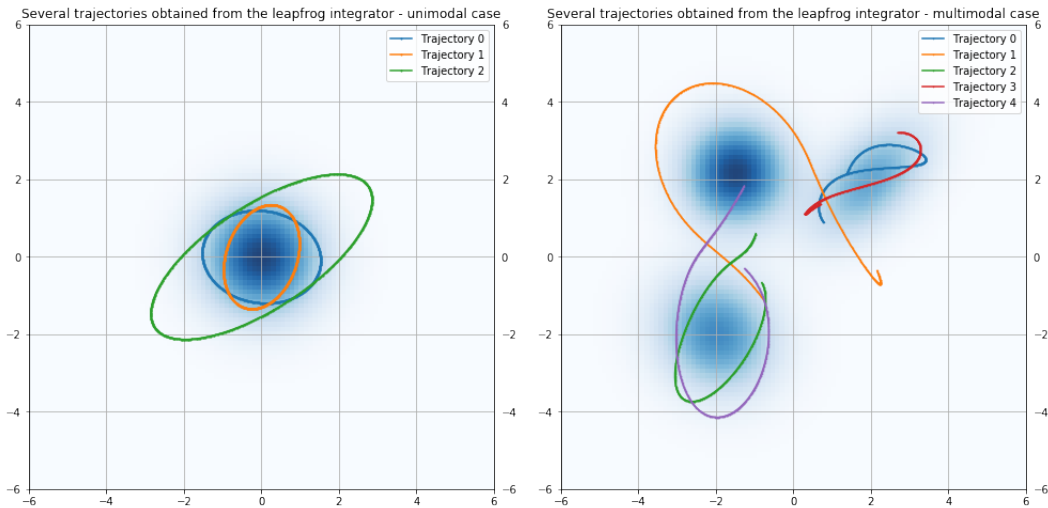
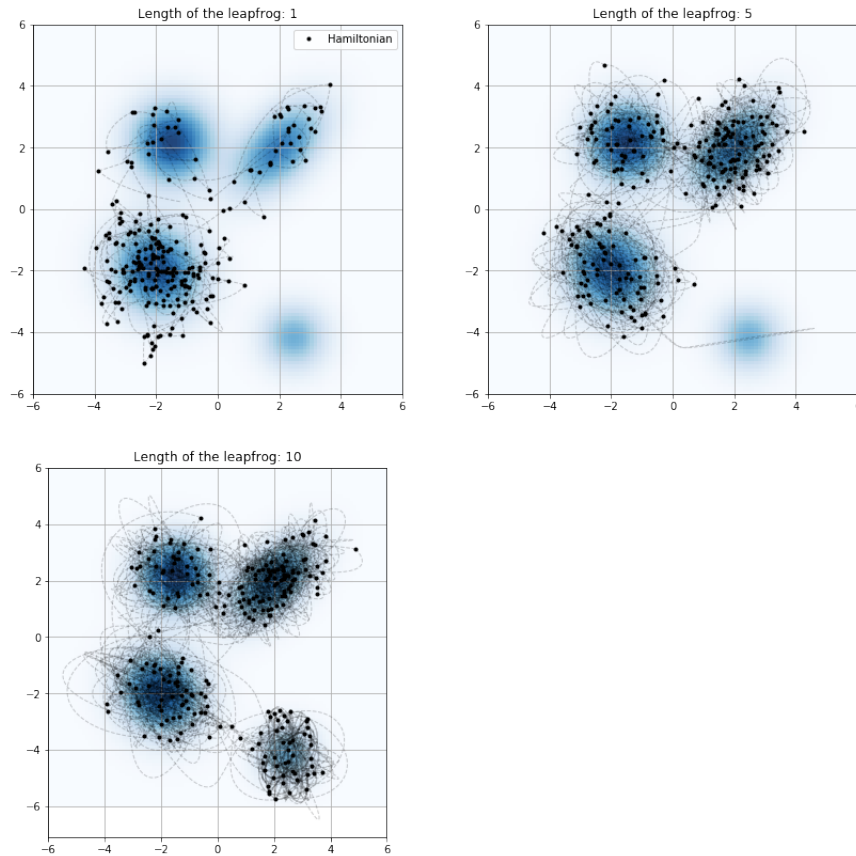


Figure 7.1.1 displays several trajectories of a HMC sampler with leapfrog integrators with various lengths when the target density a mixture of Gaussian distributions. This figure highlights the fact that the proposed moves provided by the leapfrog integrator allow to explore widely the space and to jump from a mode to another.



7.2 Exercises

Exercise 7.1. Let

$$X_t = \sigma_t Z_t, \quad \sigma_t^2 = \alpha_0 + \alpha_1 X_{t-1}^2, \quad t \geq 1$$

where the coefficients α_0, α_1 are positive and $\{Z_t : t \in \mathbb{N}\}$ is an iid sequence of random variables such that $\mathbb{E}[Z_0] = 0$, $\mathbb{E}[Z_0^2] = 1$, and $\{Z_t : t \in \mathbb{N}\}$ is independent of X_0

1. Assuming that Z_0 has the density q wrt the Lebesgue measure, show that $\{X_t : t \in \mathbb{N}\}$ is a Markov chain with transition density

$$p(x, x') = \frac{1}{\sqrt{\alpha_0 + \alpha_1 x^2}} q\left(\frac{x'}{\sqrt{\alpha_0 + \alpha_1 x^2}}\right).$$

Exercise 7.2. Let $\mu \in \mathcal{M}_1(X)$ and assume that for some function $h \in \mathcal{F}(X)$, and some constant C ,

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} h(X_k) = C, \quad \mathbb{P}_\mu - a.s.$$

Then show that for μ -almost all $x \in X$,

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} h(X_k) = C, \quad \mathbb{P}_x - a.s.$$

Exercise 7.3. In this exercise, we will show the strong Markov property: for any $\nu \in \mathcal{M}_1(\mathbb{X})$, any non-negative or bounded function h on $\mathbb{X}^{\mathbb{N}}$, any $n \in \mathbb{N}$ and any stopping time σ ,

$$\mathbb{E}_{\nu} [h \circ S^{\sigma} \mathbf{1}_{\{\sigma < \infty\}} | \mathcal{F}_{\sigma}] = \mathbb{E}_{X_{\sigma}} [h], \quad \mathbb{P}_{\nu} - a.s.$$

where $\mathcal{F}_{\sigma} = \{A \in \mathcal{F} : A \cap \{\sigma = k\} \in \mathcal{F}_k, \forall k \geq 1\}$ and $\mathcal{F}_k = \sigma(X_{0:k})$.

For any filtration (\mathcal{F}_k) on \mathcal{F} , recall that σ is a (\mathcal{F}_k) -stopping time if for all $n \in \mathbb{N}$, $\{\sigma \leq n\} \in \mathcal{F}_n$.

1. Define $\mathcal{F}_{\sigma} = \{A \in \mathcal{F} : A \cap \{\sigma = k\} \in \mathcal{F}_k, \forall k \geq 1\}$. Show that \mathcal{F}_{σ} is a σ -field.
2. Using the decomposition, $\mathbf{1}_{\{\sigma < \infty\}} = \sum_{k=0}^{\infty} \mathbf{1}_{\{\sigma = k\}}$, show the strong Markov property.

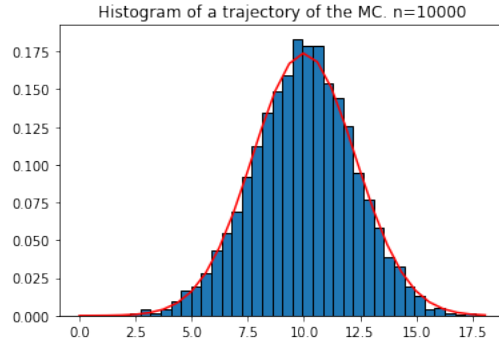
Exercise 7.4. Consider a Gaussian AR(1) process, $X_t = \mu + \phi X_{t-1} + \sigma Z_t$, where $\{Z_t : t \in \mathbb{N}\}$ is an iid sequence of standard Gaussian random variables, independent of X_0 . Assume that $|\phi| < 1$ and that X_0 is Gaussian with mean μ_0 and variance γ_0^2 .

1. Show that if X_1 has the same distribution as X_0 then

$$\begin{cases} \mu + \phi \mu_0 = \mu_0 \\ \phi^2 \gamma_0^2 + \sigma^2 = \gamma_0^2 \end{cases}$$

2. Deduce an invariant distribution for $(X_t)_{t \in \mathbb{N}}$.

Details of the numerics are given in the Jupyter Notebook.



Exercise 7.5. Consider a Markov chain whose state space $\mathbb{X} = (0, 1)$ is the open unit interval. If the chain is at x , it picks one of the two intervals $(0, x)$ or $(x, 1)$ with equal probability $1/2$, and then moves to a point y which is uniformly distributed in the chosen interval.

1. Show that this Markov chain has a transition density wrt the Lebesgue measure on the interval $(0, 1)$, which is given by

$$k(x, y) = \frac{1}{2} \frac{1}{x} \mathbf{1}_{(0,x)}(y) + \frac{1}{2} \frac{1}{1-x} \mathbf{1}_{(x,1)}(y)$$

2. Show that this Markov chain can be equivalently represented as an iterated random sequence.

$$X_t = \epsilon_t [X_{t-1} U_t] + (1 - \epsilon_t) [X_{t-1} + U_t(1 - X_{t-1})]$$

where $\{U_n : n \in \mathbb{N}\}$ and $\{\epsilon_n : n \in \mathbb{N}\}$ are iid random variables whose distribution should be given.

3. Assuming that the stationary distribution has a density p wrt the Lebesgue measure show that

$$p(y) = \frac{1}{2} \int_y^1 \frac{p(x)}{x} dx + \frac{1}{2} \int_0^y \frac{p(x)}{1-x} dx$$

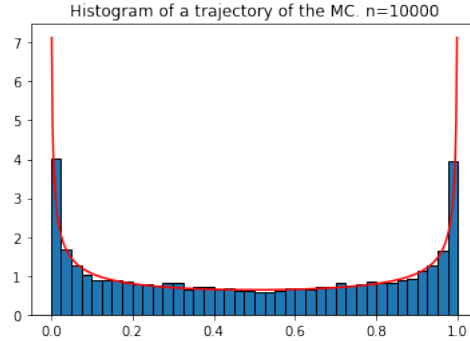
4. Deduce that

$$\int_0^z p(y)dy = 2C \arcsin(\sqrt{z})$$

for some constant C .

5. Conclude that $C = 1/\pi$.

Details of the numerics are given in the Jupyter Notebook.



Exercise 7.6. Let $\pi(dx dy) = \pi(x, y)\lambda_X(dx)\lambda_Y(dy)$ be probability measure on $(\mathbf{X} \times \mathbf{Y}, \mathcal{X} \otimes \mathcal{Y})$ where λ_X (resp. λ_Y) is σ -finite measure on $(\mathbf{X}, \mathcal{X})$ (resp. $(\mathbf{Y}, \mathcal{Y})$). Define $\pi(y|x) = \frac{\pi(x, y)}{\pi(x)}$ whenever $\pi(x) \neq 0$.

Define: $P((x, y), dx' dy') = \delta_x(dx')\pi(y'|x)\lambda_Y(dy')$. Show that P is a π -reversible Markov kernel on $(\mathbf{X} \times \mathbf{Y}) \times (\mathcal{X} \otimes \mathcal{Y})$.

Exercise 7.7. In a MH algorithm, we want to find an acceptance probability $\alpha(x, y) = f\left(\frac{\pi(y)q(y, x)}{\pi(x)q(x, y)}\right)$

1. Show that the detailed balance condition is satisfied if and only if for all $u \geq 0$, $f(u) = uf(1/u)$.
2. Show that it is sufficient to check that for all $u \in (0, 1)$, $f(u) = uf(1/u)$.
3. Find all the functions f such that the detailed balance condition is satisfied with $\alpha(x, y) = f\left(\frac{\pi(y)q(y, x)}{\pi(x)q(x, y)}\right)$.

Exercise 7.8. Let P be a Markov kernel with invariant probability measure π . Let $A \in \mathcal{X}$ such that $\pi(A) = 1$. Show that there exists $B \subset A$ such that $P(x, B) = 1$ for all $x \in B$ (i.e. such set B is said to be *absorbing* in the sense that starting from any point in B , the Markov chain stays in B forever with probability one).

Exercise 7.9. Let (X_t) be the AR(p) process defined by: $X_t = \sum_{i=1}^p a_i X_{t-i} + \sigma \epsilon_t$ for all $t \geq i$, where $\epsilon_i \stackrel{\text{i.i.d.}}{\sim} \mathcal{N}(0, 1)$ and $\sigma > 0$.

Define $Y_t = \begin{pmatrix} X_t \\ \dots \\ X_{t-p+1} \end{pmatrix}$ and show that (Y_t) is a Markov chain. Give the expression of the associated Markov kernel. Show that it admits at most one invariant probability measure.

Exercise 7.10. Let P be a Markov kernel on $\mathbf{X} \times \mathcal{X}$, admitting an invariant probability measure π . We assume that there exist two measurable positive functions V and f and a constant K such that

$$PV + f \leq V + K$$

Show that $\pi(f) < \infty$.

Exercise 7.11. In this exercise, we prove Theorem 3.4. Set $S_n = \sum_{k=0}^{n-1} h \circ T^k$, $L_n = \inf \{S_k : k \in [1 : n]\}$ and $A = \{\inf_{n \in \mathbb{N}^*} L_n = -\infty\}$. We first assume that $\mathbb{E}[h] > 0$.

1. Show that $L_n \geq h + \inf(0, L_n \circ T)$.

2. Deduce that

$$\mathbb{E}[\mathbf{1}_A h] \leq \mathbb{E}[\mathbf{1}_A (L_n)^+]$$

3. Deduce $\mathbb{P}(A) = 0$.

4. Prove The Birkhoff theorem (Theorem 3.4).

Exercise 7.12. Assume that (A1) and (A2) hold for some measurable function $V \geq 1$. We want to prove that: for all initial distributions $\nu \in \mathcal{M}_1(X)$ and all $f \in \mathcal{F}(X)$ such that $\pi(|f|) = \int_X \pi(dx) |f(x)| < \infty$,

$$\lim_{n \rightarrow \infty} n^{-1} \sum_{k=0}^{n-1} f(X_k) = \pi(f), \quad \mathbb{P}_\nu - a.s \quad (7.1)$$

1. Prove the result by combining Corollary 4.7 and Theorem 4.5 with some results in Chapter 3 (give the exact references of the results that you pick from Chapter 3)

Exercise 7.13. Consider the following discretization of the Hamiltonian dynamics.

$$\begin{aligned} p^{k+1} &= p^k - (h) \nabla U(q^k) \\ q^{k+1} &= q^k + h p^{k+1} \end{aligned} \quad (7.2)$$

1. Is it volume-preserving?

2. Can we use the flip operator trick to obtain an involution?

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