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INTERTWINING AND COMMUTATION RELATIONS FOR BIRTH-DEATH PROCESSES

DJALIL CHAFAÏ AND ALDÉRIC JOULIN

Abstract. Given a birth-death process on $\mathbb{N}$ with semigroup $(P_t)_{t\geq 0}$ and a discrete gradient ∂_u depending on a positive weight u, we establish intertwining relations of the form $\partial_u P_t = Q_t \partial_u$, where $(Q_t)_{t\geq 0}$ is the Feynman-Kac semigroup with potential V_u of another birth-death process. We provide applications when V_u is non-negative and uniformly bounded from below, including Lipschitz contraction and Wasserstein curvature, various functional inequalities, and stochastic orderings. Our analysis is naturally connected to the previous works of Caputo-Dai Pra-Posta and of Chen on birth-death processes. The proofs are remarkably simple and rely on interpolation, commutation, and convexity.

1. Introduction

Commutation relations and convexity are useful tools for the fine analysis of Markov diffusion semigroups [B-E, B, L]. The situation is more delicate on discrete spaces, due to the lack of a chain rule formula [B-L, A, Che1, J-P, B-T, Cha2, C-DP-P, Che3]. In this work, we obtain new intertwining and sub-commutation relations for a class of birth-death processes involving a discrete gradient and an auxiliary Feynman-Kac semigroup. We also provide various applications of these relations. Our analysis is naturally related to the curvature condition of Caputo-Dai Pra-Posta [C-DP-P] and to the Chen exponent of Chen [Che1, Che3]. More precisely, let us consider a birth-death process $(X_t)_{t\geq 0}$ on the state space $\mathbb{N} := \{0, 1, 2, \ldots\}$, i.e. a Markov process with transition probabilities given by

$$P_t^x(y) = \mathbb{P}_x(X_t = y) = \begin{cases} \lambda_x t + o(t) & \text{if } y = x+1, \\ \nu_x t + o(t) & \text{if } y = x-1, \\ 1 - (\lambda_x + \nu_x)t + o(t) & \text{if } y = x, \end{cases}$$

where $\lim_{t\to 0} t^{-1} o(t) = 0$. The transition rates λ and ν are respectively called the birth and death rates of the process $(X_t)_{t\geq 0}$. The process is irreducible, positive recurrent (or ergodic), and non-explosive when the rates satisfy to $\lambda > 0$ on $\mathbb{N}$ and $\nu > 0$ on $\mathbb{N}^*$ and $\nu_0 = 0$ and

$$\sum_{x=1}^{\infty} \frac{\lambda_0 \lambda_1 \cdots \lambda_{x-1}}{\nu_1 \nu_2 \cdots \nu_x} < \infty \quad \text{and} \quad \sum_{x=1}^{\infty} \left(\frac{1}{\lambda_x} + \frac{\nu_x}{\lambda_x \lambda_{x-1}} + \cdots + \frac{\nu_x \cdots \nu_1}{\lambda_x \cdots \lambda_1 \lambda_0} \right) = \infty,$$

respectively. In this case the unique stationary distribution μ of the process is reversible and is given by

$$\mu(x) = \mu(0) \prod_{y=1}^{x} \frac{\lambda_{y-1}}{\nu_y}, \ x \in \mathbb{N} \quad \text{with} \quad \mu(0) := \left(1 + \sum_{x=1}^{\infty} \frac{\lambda_0 \lambda_1 \cdots \lambda_{x-1}}{\nu_1 \nu_2 \cdots \nu_x} \right)^{-1}. \tag{1.1}$$

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Let us denote by $\mathcal{F}$ (respectively $\mathcal{F}_+$ and $\mathcal{F}_d$) the space of real-valued (respectively positive and non-negative non-decreasing) functions f on $\mathbb{N}$. The associated semigroup $(P_t)_{t\geq 0}$ is defined for any bounded or non-negative function f as

$$P_t f(x) = \mathbb{E}_x[f(X_t)] = \sum_{y=0}^{\infty} f(y) P_t^x(y), \quad x \in \mathbb{N}.$$

This family of operators is positivity preserving and contractive on $L^p(\mu)$, $p \in [1,\infty]$. Moreover, the semigroup is also symmetric in $L^2(\mu)$ since $\lambda_x \mu(x) = \nu_{1+x}\mu(1+x)$ for any $x \in \mathbb{N}$ (detailed balance equation). The generator $\mathcal{L}$ of the process is given for any $f \in \mathcal{F}$ and $x \in \mathbb{N}$ by

$$\begin{aligned}\mathcal{L}f(x) &= \lambda_x \left(f(x+1) - f(x)\right) + \nu_x \left(f(x-1) - f(x)\right) \\ &= \lambda_x \, \partial f(x) + \nu_x \, \partial^* f(x),\end{aligned}$$

where ∂ and ∂^* are respectively the forward and backward discrete gradients on $\mathbb{N}$:

$$\partial f(x) := f(x+1) - f(x) \quad \text{and} \quad \partial^* f(x) := f(x-1) - f(x).$$

Our approach is inspired from the remarkable properties of two special birth-death processes: the $M/M/1$ and the $M/M/\infty$ queues. The $M/M/\infty$ queue has rates $\lambda_x = \lambda$ and $\nu_x = \nu x$ for positive constants λ and ν. It is positive recurrent and its stationary distribution is the Poisson measure μ_ρ with mean $\rho = \lambda/\mu$. If $\mathscr{B}_{x,p}$ stands for the binomial distribution of size $x \in \mathbb{N}$ and parameter $p \in [0,1]$, the $M/M/\infty$ process satisfies for every $x \in \mathbb{N}$ and $t \geq 0$ to the Mehler type formula

$$\mathscr{L}(X_t | X_0 = x) = \mathscr{B}_{x,e^{-\nu t}} * \mu_{\rho(1-e^{-\nu t})}. \tag{1.2}$$

The $M/M/1$ queening process has rates $\lambda_x = \lambda$ and $\nu_x = \nu \mathbf{1}_{\mathbb{N}\setminus\{0\}}$ where $0 < \lambda < \nu$ are constants. It is a positive recurrent random walk on $\mathbb{N}$ reflected at 0. Its stationary distribution μ is the geometric measure with parameter $\rho := \lambda/\nu$ given by $\mu(x) = (1-\rho)\rho^x$ for all $x \in \mathbb{N}$. A remarkable common property shared by the $M/M/1$ and $M/M/\infty$ processes is the intertwining relation

$$\partial \mathcal{L} = \mathcal{L}^V \partial \tag{1.3}$$

where $\mathcal{L}^V = \mathcal{L} - V$ is the discrete Schrödinger operator with potential V given by

- $V(x) := \nu$ in the case of the $M/M/\infty$ queue
- $V(x) := \nu \mathbf{1}_{\{0\}}(x)$ for the $M/M/1$ queue.

Since $V \geq 0$ in these two cases, the operator $\mathcal{L}^V$ is the generator of a birth-death process with killing rate V and the associated Feynman-Kac semigroup $(P_t^V)_{t\geq 0}$ is given by

$$P_t^V f(x) = \mathbb{E}_x \left[f(X_t) \exp\left(- \int_0^t V(X_s) ds \right) \right].$$

The intertwining relation (1.3) is the infinitesimal version at time $t = 0$ of the semigroup intertwining

$$\partial P_t f(x) = P_t^V \partial f(x) = \mathbb{E}_x \left[\partial f(X_t) \, \exp\left(- \int_0^t V(X_s) \, ds \right) \right]. \tag{1.4}$$

Conversely, one may deduce (1.4) from (1.3) by using a semigroup interpolation. Namely, if we consider $s \in [0,t] \mapsto J(s) := P_s^V \partial P_{t-s} f$ with V as above, then (1.4) rewrites as $J(0) = J(t)$ and (1.4) follows from (1.3) since

$$J'(s) = P_s^V \left(\mathcal{L}^V \partial P_{t-s} f - \partial \mathcal{L} P_{t-s} f \right) = 0.$$

In section 2, we obtain by using semigroup interpolation an intertwining relation similar to (1.4) for more general birth-death processes. By using convexity as an additional ingredient, we also obtain sub-commutation relations. These results are new and have

several applications explored in section 3, including Lipschitz contraction and Wasserstein curvature (section 3.1), functional inequalities including Poincaré, entropic, isoperimetric and transportation-information inequalities (section 3.2), hitting time of the origin for the $M/M/1$ queue (section 3.3), convex domination and stochastic orderings (section 3.4).

2. Intertwining relations and sub-commutations

Let us fix some $u \in \mathcal{F}_+$. The u-modification of the original process $(X_t)_{t\geq 0}$ is a birth-death process $(X_{u,t})_{t\geq 0}$ with semigroup $(P_{u,t})_{t\geq 0}$ and generator $\mathcal{L}_u$ given by

$$\mathcal{L}_u f(x) = \lambda_x^u \, \partial f(x) + \nu_x^u \, \partial^* f(x),$$

where the birth and death rates are respectively given by

$$\lambda_x^u := \frac{u_{x+1}}{u_x} \, \lambda_{x+1} \quad \text{and} \quad \nu_x^u := \frac{u_{x-1}}{u_x} \, \nu_x.$$

One can check that the measure $\lambda u^2 \mu$ is symmetric for $(X_{u,t})_{t\geq 0}$. As consequence, the process $(X_{u,t})_{t\geq 0}$ is positive recurrent if and only if λu^2 is μ-integrable. From now on, we restrict to the minimal solution corresponding to the forward and backward Kolmogorov equations given as follows: for any function $f \in \mathcal{F}$ with finite support and $t \geq 0$,

$$\frac{d}{dt} P_{u,t} f = P_{u,t} \mathcal{L}_u f = \mathcal{L}_u P_{u,t} f,$$

cf. [Che2, th. 2.21]. In order to justify in all circumstances the computations present in these notes, we need to extend these identities to bounded functions f. Although it is not restrictive for the backward equation, the forward equation is more subtle and requires an additional integrability assumption. From now on, we always assume that the transition rates λ^u and ν^u and also the potential V_u are $P_{u,t}$ integrable.

We define the discrete gradient ∂_u and the potential V_u by

$$\partial_u := (1/u)\partial \quad \text{and} \quad V_u(x) := \nu_{x+1} - \nu_x^u + \lambda_x - \lambda_x^u.$$

Let $\varphi : \mathbb{R} \to \mathbb{R}$ be a smooth convex function such that for some constant $c > 0$, and for all $r \in \mathbb{R}$,

$$\varphi'(r) r \geq c \varphi(r). \tag{2.1}$$

In particular, the behavior at infinity is at least polynomial of degree c.

Let us state our first main result about intertwining and sub-commutation relations between the original process $(X_t)_{t\geq 0}$ and its u-modification $(X_{u,t})_{t\geq 0}$. To the knowledge of the authors, this result was not known. A connection to Chen's results on birth-death processes [Che2] is given in section 3 in the sequel.

Theorem 2.1 (Intertwining and sub-commutation)**.** *Assume that the process is irreducible, non-explosive and that the potential V_u is lower bounded. Let $f \in \mathcal{F}$ be such that $\sup_{y\in\mathbb{N}} |\partial_u f(y)| < \infty$, and let $x \in \mathbb{N}$ and $t \geq 0$. Then the following intertwining relation holds:*

$$\partial_u P_t f(x) \;=\; P_{u,t}^{V_u} \partial_u f(x) \;=\; \mathbb{E}_x \left[\partial_u f(X_{u,t}) \, \exp\left(- \int_0^t V_u(X_{u,s}) \, ds \right) \right]. \tag{2.2}$$

Moreover, if $V_u \geq 0$ then we have the sub-commutation relation

$$\varphi\left(\partial_u P_t f\right)(x) \leq \mathbb{E}_x \left[\varphi(\partial_u f)(X_{u,t}) \, \exp\left(- \int_0^t c V_u(X_{u,s}) \, ds \right) \right]. \tag{2.3}$$

Proof. The key point is the following intertwining relation

$$\partial_u \mathcal{L} = \mathcal{L}_u^{V_u} \partial_u, \tag{2.4}$$

where $\mathcal{L}_u$ is the generator of the u-modification process $(X_{u,t})_{t\geq 0}$ and $\mathcal{L}_u^{V_u} := \mathcal{L}_u - V_u$ is the discrete Schrödinger operator with potential V_u. Note that the relation (2.4) is

somewhat similar to (1.3) and follows by simple computations. To prove (2.2) from (2.4), we proceed as we did to obtain (1.4) from (1.3). If we define

$$s \in [0,t] \mapsto J(s) := P_{u,s}^{V_u} \partial_u P_{t-s} f,$$

then (2.2) rewrites as $J(0) = J(t)$. Hence it suffices to show that J is constant. By [Che1] we know that if $\partial_u f$ is bounded then $\partial_u P_{t-s} f$ is also bounded. Hence using the Kolmogorov equations and (2.4), we obtain

$$J'(s) = P_{u,s}^{V_u} \left(\mathcal{L}_u^{V_u} \partial_u P_{t-s} f - \partial_u \mathcal{L} P_{t-s} f \right) = 0,$$

yielding to the intertwining relation (2.2).
Now let us prove the sub-commutation relation (2.3) by adapting the previous interpolation method, under the additional assumption $V_u \geq 0$. Denoting

$$s \in [0,t] \mapsto J_c(s) := P_{u,s}^{cV_u} \varphi(\partial_u P_{t-s} f),$$

then (2.3) rewrites as $J_c(0) \leq J_c(t)$. Hence let us show that J_c is a non-decreasing function. Since $\varphi(\partial_u P_{t-s} f)$ is bounded, we have by the Kolmogorov equations:

$$J_c'(s) = P_{u,s}^{cV_u}(T) \quad \text{where} \quad T = \mathcal{L}_u^{cV_u} \varphi(\partial_u P_{t-s} f) - \varphi'(\partial_u P_{t-s} f)\, \partial_u \mathcal{L} P_{t-s} f.$$

Letting $g_u = \partial_u P_{t-s} f$, we obtain, by using (2.4),

$$\begin{aligned} T &= \mathcal{L}_u^{cV_u} \varphi(g_u) - \varphi'(g_u) \mathcal{L}_u^{V_u} g_u \\ &= \lambda^u \left(\partial \varphi(g_u) - \varphi'(g_u) \partial g_u \right) + \nu^u \left(\partial^* \varphi(g_u) - \varphi'(g_u) \partial^* g_u \right) + V_u \left(\varphi'(g_u) g_u - c\varphi(g_u) \right) \\ &= \lambda^u A^\varphi(g_u, \partial g_u) + \nu^u A^\varphi(g_u, \partial^* g_u) + V_u \left(\varphi'(g_u) g_u - c\varphi(g_u) \right) \end{aligned}$$

where $A^\varphi(r,s) = \varphi(r+s) - \varphi(r) - \varphi'(r)s$ is the so-called A-transform of φ studied in [Cha2] also known in convex analysis as the Bregman divergence associated to φ [Br]. Note that $g_u + \partial g_u = g_u(\cdot + 1)$ and $g_u + \partial^* g_u = g_u(\cdot - 1)$. Now, since φ is convex, we have $A^\varphi \geq 0$. Moreover, using (2.1) and $V_u \geq 0$ we obtain that $T \geq 0$. Finally, we get the desired result since the Feynman-Kac semigroup $(P_{u,t}^{cV_u})_{t \geq 0}$ is positivity preserving. □

Remark 2.2 (Ergodic condition)**.** *The potential V_u in theorem 2.1 is assumed to be lower bounded. When it is positive, the so-called Chen exponent $\inf_{y \in \mathbb{N}} V_u(y)$ is related to the exponential ergodicity of the original process $(X_t)_{t \geq 0}$, cf.* [Che1]*. However identity* (2.2) *does not require such an ergodic assumption. A nice study of the exponential decay of birth-death processes was recently studied by Chen in* [Che3]*, with special emphasis on non-ergodic situations including transient cases.*

Remark 2.3 (Case of equality)**.** *According to the proof of theorem 2.1, the assumption $V_u \geq 0$ can be dropped if the convex function φ realizes the equality in* (2.1)*. Such an observation was expected since in this case the use of Hölder's inequality in* (2.2) *entails the desired result.*

Remark 2.4 (Propagation of monotonicity)**.** *The identity* (2.2) *provides a new proof of the propagation of monotonicity* [S, prop. 4.2.10]*: if $f \in \mathcal{F}_d$ then $P_t f \in \mathcal{F}_d$ for all $t \geq 0$. See section 3.4 for an interpretation in terms of stochastic ordering.*

Remark 2.5 (Other gradients)**.** *Theorem 2.1 possesses a natural analogue for the discrete backward gradient ∂^*. We ignore if there exists a useful "balanced" intertwining relation involving a combination of both forward and backward gradients.*

Remark 2.6 (Higher dimensional spaces)**.** *The extension of theorem 2.1 to higher dimensional discrete processes such as queuing networks or interacting particles systems arising in statistical mechanics is a very natural question, but seems to be technically difficult. However a first step has been emphasized by Wu in his study of functional inequalities for*

Gibbs measures through the Dobrushin uniqueness condition: see step 1 in the proof of proposition 2.5 in [W].

Our second new result below complements the previous one for the case $u = 1$. Let $\mathcal{I}$ be an open interval of $\mathbb{R}$ and let $\varphi : \mathcal{I} \to \mathbb{R}$ be a smooth convex function such that $\varphi'' > 0$ and $-1/\varphi''$ is convex on $\mathcal{I}$. Following the notations of [Cha2], we define on the convex subset $\mathcal{A}_{\mathcal{I}} := \{(r, s) \in \mathbb{R}^2 : (r, r + s) \in \mathcal{I} \times \mathcal{I}\}$ the non-negative function B^φ on $\mathcal{A}_{\mathcal{I}}$ by

$$B^\varphi(r, s) := (\varphi'(r + s) - \varphi'(r))\, s, \quad (r, s) \in \mathcal{A}_{\mathcal{I}}.$$

By theorem 4.4 in [Cha2], B^φ is convex on $\mathcal{A}_{\mathcal{I}}$. Some interesting examples of such functionals will be given in section 3.2 below.

Theorem 2.7 (Sub-commutation for 1-modification)**.** *Assume that the process is irreducible and non-explosive. If the transition rate λ is non-increasing and ν is non-decreasing then for any function $f \in \mathcal{F}$ such that $\sup_{y\in\mathbb{N}} |\partial f(y)| < \infty$ and for any $t \geq 0$,*

$$B^\varphi\left(P_t f, \partial P_t f\right) \leq P_{1,t}^{V_1} B^\varphi(f, \partial f) \tag{2.5}$$

where the non-negative potential is $V_1 := \partial(\nu - \lambda)$.

Proof. Under our assumption, the two processes $(X_t)_{t\geq 0}$ and $(X_{1,t})_{t\geq 0}$ are non-explosive. By using standard approximation procedures, one may assume that f has finite support. If we define $s \in [0, t] \mapsto J(s) := P_{1,s}^{V_1} B^\varphi(P_{t-s} f, \partial P_{t-s} f)$ we see that (2.5) rewrites as $J(0) \leq J(t)$. Denote $F = P_{t-s} f$ and $G = \partial P_{t-s} f = \partial F$. Since $B^\varphi(F, G)$ is bounded, the Kolmogorov equations are available and using (2.4) with the constant function $u = 1$, we have $J'(s) = P_{1,s}^{V_1}(T)$ with

$$\begin{aligned}
T &= \mathcal{L}_1^{V_1} B^\varphi(F, G) - \frac{\partial}{\partial x} B^\varphi(F, G)\, \mathcal{L}F - \frac{\partial}{\partial y} B^\varphi(F, G)\, \mathcal{L}_1^{V_1} G \\
&= \lambda^1 \partial B^\varphi(F, G) - \lambda \frac{\partial}{\partial x} B^\varphi(F, G)\, \partial F - \lambda^1 \frac{\partial}{\partial y} B^\varphi(F, G)\, \partial G \\
&\quad + \nu^1 \partial^* B^\varphi(F, G) - \nu \frac{\partial}{\partial x} B^\varphi(F, G)\, \partial^* F - \nu^1 \frac{\partial}{\partial y} B^\varphi(F, G)\, \partial^* G \\
&\quad + \partial(\nu - \lambda) \left(\frac{\partial}{\partial y} B^\varphi(F, G)\, G - B^\varphi(F, G) \right) \\
&\geq \partial\nu \left(\frac{\partial}{\partial y} B^\varphi(F, G)\, G - B^\varphi(F, G) \right) \\
&\quad - \partial\lambda \left(\frac{\partial}{\partial y} B^\varphi(F, G)\, G - \frac{\partial}{\partial x} B^\varphi(F, G)\, G - B^\varphi(F, G) \right),
\end{aligned}$$

and where in the last line we used the convexity of the bivariate function B^φ. Moreover, since the birth and death rates λ and ν are respectively non-increasing and non-decreasing on the one hand, and using once again convexity on the other hand, we get

$$\frac{\partial}{\partial y} B^\varphi(F, G)\, G \geq \begin{cases} \frac{\partial}{\partial x} B^\varphi(F, G)\, G + B^\varphi(F, G) \\ B^\varphi(F, G) \end{cases}$$

from which we deduce that T is non-negative and thus J is non-decreasing. □

Remark 2.8 (Diffusion case)**.** *Actually, the intertwining relations above have their counterpart in continuous state space, as suggested by the so-called Witten Laplacian method*

used for the analysis of Langevin-type diffusion processes, see for instance Helffer's book [H]. *Let $\mathcal{A}$ be the generator of a one-dimensional real-valued diffusion $(X_t)_{t\geq 0}$ of the type*

$$\mathcal{A}f = \sigma^2 f'' + bf',$$

where f and the two functions σ, b are sufficiently smooth. Given a smooth positive function a on $\mathbb{R}$, the gradient of interest is $\nabla_a f = a\, f'$. Denote $(P_t)_{t\geq 0}$ the associated diffusion semigroup. Then it is not hard to adapt to the continuous case the argument of theorem 2.1 to show that the following intertwining relation holds:

$$\nabla_a P_t f(x) = \mathbb{E}_x \left[\nabla_a f(X_{a,t}) \exp\left(- \int_0^t V_a(X_{a,s})\, ds \right) \right].$$

Here $(X_{a,t})_{t\geq 0}$ is a new diffusion process with generator

$$\mathcal{A}_a f = \sigma^2 f'' + b_a f'$$

and drift b_a and potential V_a given by

$$b_a := 2\sigma\sigma' + b - 2\sigma^2 \frac{a'}{a} \quad \text{and} \quad V_a := \sigma^2 \frac{a''}{a} - b' + \frac{a'}{a} b_a.$$

In particular, if the weight $a = \sigma$, where σ is assumed to be positive, then the two processes above have the same distribution and by Jensen's inequality, we obtain

$$|\nabla_\sigma P_t f(x)| \leq \mathbb{E}_x \left[|\nabla_\sigma f(X_t)| \exp\left(- \int_0^t \left(\sigma\sigma'' - b' + b \frac{\sigma'}{\sigma} \right)(X_s)\, ds \right) \right].$$

Hence under the assumption that there exists a constant ρ such that

$$\inf \sigma\sigma'' - b' + b\frac{\sigma'}{\sigma} \geq \rho,$$

then we get $|\nabla_\sigma P_t f| \leq e^{-\rho t}\, P_t |\nabla_\sigma f|$. This type of sub-commutation relation is at the heart of the Bakry-Émery calculus [B-E, B, L]. *See also* [M-T] *for a nice study of functional inequalities for the invariant measure under the condition $\rho = 0$. However, as we will see in remark 3.6 below, such a choice of the weight is not really adapted when studying the optimal constant in the Poincaré inequality.*

3. Applications

This section is devoted to applications of theorems 2.1 and 2.7.

3.1. **Lipschitz contraction and Wasserstein curvature.** Theorem 2.1 allows to recover a result of Chen [Che1] on the contraction property of the semigroup on the space of Lipschitz functions. Indeed, the intertwining (2.2) can be used to derive bounds on the Wasserstein curvature of the birth-death process, without using the coupling technique emphasized by Chen. For a distance d on $\mathbb{N}$, we denote by $\mathcal{P}_d(\mathbb{N})$ the set of probability measures ξ on $\mathbb{N}$ such that $\sum_{x\in\mathbb{N}} d(x, x_0)\xi(x) < \infty$ for some (or equivalently for all) $x_0 \in \mathbb{N}$. We recall that the Wasserstein distance between two probability measures $\mu_1, \mu_2 \in \mathcal{P}_d(\mathbb{N})$ is defined by

$$\mathcal{W}_d(\mu_1, \mu_2) = \inf_{\gamma \in \mathrm{Marg}(\mu_1,\mu_2)} \int_{\mathbb{N}} \int_{\mathbb{N}} d(x, y)\gamma(dx, dy), \tag{3.1}$$

where $\mathrm{Marg}(\mu_1, \mu_2)$ is the set of probability measures on $\mathbb{N}^2$ such that the marginal distributions are μ_1 and μ_2, respectively. The Kantorovich-Rubinstein duality [V, th. 5.10] gives

$$\mathcal{W}_d(\mu_1, \mu_2) = \sup_{g \in \mathrm{Lip}_1(d)} \int_{\mathbb{N}} g\, d(\mu_1 - \mu_2), \tag{3.2}$$

where $\mathrm{Lip}(d)$ is the set of Lipschitz function g with respect to the distance d, i.e.

$$\|g\|_{\mathrm{Lip}(d)} := \sup_{\substack{x,y\in\mathbb{N}\\ x\neq y}} \frac{|g(x)-g(y)|}{d(x,y)} < \infty,$$

and $\mathrm{Lip}_1(d)$ consists of 1-Lipschitz functions. We assume that the kernel $P_t^x \in \mathcal{P}_d(\mathbb{N})$ for every $x \in \mathbb{N}$ and $t \geq 0$ so that the semigroup is well-defined on $\mathrm{Lip}(d)$. The Wasserstein curvature of $(X_t)_{t\geq 0}$ with respect to a given distance d is the optimal (largest) constant σ in the following contraction inequality:

$$\|P_t\|_{\mathrm{Lip}(d)\to\mathrm{Lip}(d)} \leq e^{-\sigma t}, \quad t \geq 0. \tag{3.3}$$

Here $\|P_t\|_{\mathrm{Lip}(d)\to\mathrm{Lip}(d)}$ denotes the supremum of $\|P_t f\|_{\mathrm{Lip}(d)}$ when f runs over $\mathrm{Lip}_1(d)$. It is actually equivalent to the property that

$$\mathcal{W}_d(P_t^x, P_t^y) \leq e^{-\sigma t}\, d(x,y), \quad x,y \in \mathbb{N}, \quad t \geq 0.$$

If the optimal constant is positive, then the process is positive recurrent and the semigroup converges exponentially fast in Wasserstein distance $\mathcal{W}_d$ to the stationary distribution μ [Che2, th. 5.23].

Let $\rho \in \mathcal{F}_+$ be an increasing function and define $u \in \mathcal{F}_+$ as $u_x := \rho(x+1) - \rho(x)$. The metric under consideration in the forthcoming analysis is

$$d_u(x,y) = |\rho(x) - \rho(y)|.$$

Hence u remains for the distance between two consecutive points. In particular the space of functions f for which the intertwining relation of theorem 2.1 is available is actually $\mathrm{Lip}(d_u)$. Then it is shown in [Che1, J] by coupling arguments that the Wasserstein curvature σ_u with respect to the distance d_u is given by the Chen exponent, i.e.

$$\sigma_u = \inf_{x\in\mathbb{N}} \ \nu_{x+1} - \nu_x \frac{u_{x-1}}{u_x} + \lambda_x - \lambda_{x+1} \frac{u_{x+1}}{u_x}.$$

The following corollary of theorem 2.1 allows to recover this result via an intertwining relation.

Corollary 3.1 (Contraction and curvature)**.** *Assume that the potential V_u is lower bounded. Then with the notations of theorem 2.1, for any $t \geq 0$,*

$$\|P_t\|_{\mathrm{Lip}(d_u)\to\mathrm{Lip}(d_u)} = \|P_t\rho\|_{\mathrm{Lip}(d_u)} = \sup_{x\in\mathbb{N}} \mathbb{E}_x\left[\exp\left(-\int_0^t V_u(X_{u,s})\,ds\right)\right]. \tag{3.4}$$

In particular, the contraction inequality (3.3) *is satisfied with the optimal constant*

$$\sigma_u = \inf_{y\in\mathbb{N}} V_u(y). \tag{3.5}$$

Proof. Let $f \in \mathrm{Lip}_1(d_u)$ be a 1-Lipschitz function with respect to the distance d_u. For any $y, z \in \mathbb{N}$ such that $y < z$ (without loss of generality), we have by the intertwining identity (2.2) of theorem 2.1 and Jensen's inequality,

$$\begin{aligned}
|P_t f(z) - P_t f(y)| &\leq \sum_{x=y}^{z-1} u_x\, |\partial_u P_t f(x)| \\
&\leq \sum_{x=y}^{z-1} u_x\, \mathbb{E}_x\left[|\partial_u f(X_{u,t})| \exp\left(-\int_0^t V_u(X_{u,s})\,ds\right)\right] \\
&\leq d_u(z,y) \sup_{x\in\mathbb{N}} \mathbb{E}_x\left[\exp\left(-\int_0^t V_u(X_{u,s})\,ds\right)\right],
\end{aligned}$$

so that dividing by $d_u(z,y)$ and taking suprema entail the inequality:

$$\|P_t\|_{\mathrm{Lip}(d_u)\to\mathrm{Lip}(d_u)} \leq \sup_{x\in\mathbb{N}} \mathbb{E}_x\left[\exp\left(-\int_0^t V_u(X_{u,s})\,ds\right)\right].$$

Finally, since by remark 2.4 the semigroup $(P_t)_{t\geq 0}$ propagates monotonicity, the right-hand-side of the latter inequality is nothing but $\|P_t\rho\|_{\mathrm{Lip}(d_u)}$, showing that the supremum over $\mathrm{Lip}_1(d_u)$ is attained for the function ρ. The proof of equation (3.4) is achieved.

To establish (3.5), note that it suffices to get part $\leq$ since the other inequality follows from (3.4). Applying (2.2) to the function ρ which is trivially in $\mathrm{Lip}_1(d_u)$, we have for all $x\in\mathbb{N}$,

$$\sigma_u \leq -\frac{1}{t}\log \mathbb{E}_x\left[\exp\left(-\int_0^t V_u(X_{u,s})\,ds\right)\right], \quad t\geq 0,$$

and taking the limit as $t\to 0$ entails the inequality $\sigma_u \leq V_u(x)$, available for all $x\in\mathbb{N}$. The proof of (3.5) is now complete. □

Remark 3.2 (Pointwise gradient estimates for the Poisson equation)**.** *The argument used in the proof of corollary 3.1 allows also to obtain pointwise gradient estimates for the solution of the Poisson equation at the heart of Chen-Stein methods* [B-H-J, Br-X, B-X, Sch]. *More precisely, let us assume that d_u is such that $\rho\in L^1(\mu)$. For any centered function $f\in\mathrm{Lip}_1(d_u)$, let us consider the Poisson equation $-\mathcal{L}g=f$, where the unknown is g. Then under the assumption $\sigma_u>0$, there exists a unique centered solution $g_f\in\mathrm{Lip}(d_u)$ to this equation given by the formula $g_f=\int_0^\infty P_t f\,dt$. We have for any $x\in\mathbb{N}$ the following estimate (compare with* [L-M, th. 2.1]*):*

$$\begin{aligned}\sup_{f\in\mathrm{Lip}_1(d_u)} |\partial g_f(x)| &= \sup_{f\in\mathrm{Lip}_1(d_u)} u_x \int_0^\infty |\partial_u P_t f(x)|\,dt\\ &= u_x\int_0^\infty \partial_u P_t\rho(x)\,dt\\ &= u_x\int_0^\infty \mathbb{E}_x\left[\exp\left(-\int_0^t V_u(X_{u,s})\,ds\right)\right]dt\\ &\leq \frac{u_x}{\sigma_u}.\end{aligned}$$

3.2. **Functional inequalities.** Theorems 2.1 and 2.7 allow to establish a whole family of discrete functional inequalities. We define the bilinear symmetric form Γ on $\mathcal{F}$ by

$$\Gamma(f,g) := \frac{1}{2}\left(\mathcal{L}(fg)-f\mathcal{L}g-g\mathcal{L}f\right) = \frac{1}{2}\left(\lambda\,\partial f\,\partial g+\nu\,\partial^* f\,\partial^* g\right).$$

Under the positive recurrence assumption, the associated Dirichlet form acting on its domain $\mathcal{D}(\mathcal{E}_\mu)\times\mathcal{D}(\mathcal{E}_\mu)$ is given by

$$\mathcal{E}_\mu(f,g) := \frac{1}{2}\int_{\mathbb{N}}\Gamma(f,g)\,d\mu = \int_{\mathbb{N}}\lambda\,\partial f\,\partial g\,d\mu$$

where the second equality comes from the reversibility of the process. Here the domain $\mathcal{D}(\mathcal{E}_\mu)$ corresponds to the subspace of functions $f\in L^2(\mu)$ such that $\mathcal{E}_\mu(f,f)$ is finite. The stationary distribution μ is said to satisfy the Poincaré inequality with constant c if for any function $f\in\mathcal{D}(\mathcal{E}_\mu)$,

$$c\,\mathrm{Var}_\mu(f)\leq \mathcal{E}_\mu(f,f), \tag{3.6}$$

where $\mathrm{Var}_\mu(f) := \mu(f^2)-\mu(f)^2$ and $\mu(f) := \int_{\mathbb{N}} f\,d\mu$. The optimal (largest) constant c_{P} is the spectral gap of $\mathcal{L}$, i.e. the first non-trivial eigenvalue of the operator $-\mathcal{L}$. The constant c_{P} governs the $L^2(\mu)$ exponential decay to the equilibrium of the semigroup: for all $f\in L^2(\mu)$ and $t\geq 0$,

$$\|P_t f-\mu(f)\|_{L^2(\mu)} \leq e^{-c_{\mathrm{P}}t}\,\|f-\mu(f)\|_{L^2(\mu)}.$$

Several years ago, Chen used a coupling method which provides the following formula for the spectral gap:

$$c_{\mathrm{P}} = \sup_{u \in \mathcal{F}_+} \sigma_u$$

where σ_u is the Wasserstein curvature of section 3.1 or, in other words, the Chen exponent. It corresponds to theorem 1.1 in [Che1], equation (1.4). The following corollary of theorem 2.1 allows to recover the $\geq$ part of Chen's formula.

Corollary 3.3 (Spectral gap and Wasserstein curvatures)**.** *Assume that there exists some function $u \in \mathcal{F}_+$ such that the associated Wasserstein curvature σ_u is positive. Then the Poincaré inequality* (3.6) *holds with constant* $\sup_{u \in \mathcal{F}_+} \sigma_u$*, or in other words*

$$c_{\mathrm{P}} \geq \sup_{u \in \mathcal{F}_+} \sigma_u.$$

Proof. Since there exists some function $u \in \mathcal{F}_+$ such that the Wasserstein curvature σ_u is positive, the process is positive recurrent. By proposition 6.59 in [Che2], the subspace of $\mathcal{D}(\mathcal{E}_\mu)$ consisting of functions with finite support is a core of the Dirichlet form and thus we can assume without loss of generality that f has finite support. We have

$$\begin{aligned}
\mathrm{Var}_\mu(f) &= -\int_{\mathbb{N}} \int_0^\infty \frac{d}{dt} (P_t f)^2 \, dt \, d\mu \\
&= -2 \int_{\mathbb{N}} \int_0^\infty P_t f \, \mathcal{L} P_t f \, dt \, d\mu \\
&= 2 \int_0^\infty \int_{\mathbb{N}} \lambda \, u^2 \, (\partial_u P_t f)^2 \, d\mu \, dt \\
&\leq 2 \int_0^\infty e^{-2\sigma_u t} \int_{\mathbb{N}} \lambda \, u^2 \, P_{u,t} (\partial_u f)^2 \, d\mu \, dt,
\end{aligned}$$

where in the last line we used theorem 2.1 with the convex function $\varphi(x) = x^2$. Now the measure $\lambda u^2 \mu$ is invariant for the semigroup $(P_{u,t})_{t \geq 0}$, so that we have

$$\begin{aligned}
\mathrm{Var}_\mu(f) &\leq 2 \int_0^\infty e^{-2\sigma_u t} \int_{\mathbb{N}} \lambda \, u^2 \, (\partial_u f)^2 \, d\mu \, dt \\
&= \frac{1}{\sigma_u} \int_{\mathbb{N}} \lambda \, (\partial f)^2 \, d\mu \\
&= \frac{1}{\sigma_u} \, \mathcal{E}_\mu(f, f),
\end{aligned}$$

where in the second line we used $\sigma_u > 0$. The proof of the Poincaré inequality is complete. □

Remark 3.4 ($M/M/\infty$ and $M/M/1$)**.** *The spectral gap of the $M/M/\infty$ and $M/M/1$ processes is well-known* [Che1]*. Corollary 3.3 allows to recover it easily. Indeed, in the $M/M/\infty$ case, the value $c_{\mathrm{P}} = \nu$ can be obtained as follows: choose the constant weight $u = 1$ to get $c_{\mathrm{P}} \geq \nu$, and notice that the equality holds for affine functions. For a positive recurrent $M/M/1$ process, i.e. $\lambda < \nu$, we obtain $c_{\mathrm{P}} \geq (\sqrt{\lambda} - \sqrt{\nu})^2$ by choosing the weight $u_x := (\nu/\lambda)^{x/2}$, whereas the equality asymptotically holds in* (3.6) *as $\kappa \to \sqrt{\nu/\lambda}$ for the functions κ^x, $x \in \mathbb{N}$. We conclude that $c_{\mathrm{P}} = (\sqrt{\lambda} - \sqrt{\nu})^2$.*

Remark 3.5 (Alternative method for $M/M/1$)**.** *In the $M/M/1$ case, let us recover the bound $c_{\mathrm{P}} \geq (\sqrt{\lambda} - \sqrt{\nu})^2$ by using a different method. Letting $\rho(x) := x$ for $x \in \mathbb{N}$ and*

$g = f - f(0)$ for a given function $f \in \mathcal{D}(\mathcal{E}_\mu)$, we have

$$\begin{aligned}\int_{\mathbb{N}} g^2\,d\mu &= \frac{1}{\nu-\lambda}\int_{\mathbb{N}} g^2\,(-\mathcal{L}\rho)\,d\mu\\ &= \frac{1}{\nu-\lambda}\,\mathcal{E}_\mu(g^2,\rho)\\ &= \frac{\lambda}{\nu-\lambda}\int_{\mathbb{N}} \partial(g^2)\,\partial\rho\,d\mu\\ &= \frac{\lambda}{\nu-\lambda}\int_{\mathbb{N}} \left(2g\,\partial f + (\partial f)^2\right)\,d\mu\\ &\le \frac{\lambda}{\nu-\lambda}\left(2\sqrt{\int_{\mathbb{N}} g^2\,d\mu}\sqrt{\int_{\mathbb{N}}(\partial f)^2\,d\mu} + \int_{\mathbb{N}}(\partial f)^2\,d\mu\right),\end{aligned}$$

where in the last inequality we used Cauchy-Schwarz' inequality. Solving this polynomial of degree 2 entails the inequality

$$\int_{\mathbb{N}} g^2\,d\mu \le \frac{\lambda}{(\sqrt{\lambda}-\sqrt{\nu})^2}\int_{\mathbb{N}}(\partial f)^2\,d\mu.$$

Finally using the inequality $\mathrm{Var}_\mu(f) \le \int_{\mathbb{N}} g^2\,d\mu$*, we get the result.*

Remark 3.6 (Diffusion case)**.** *As mentioned in remark 2.8, the argument above leading to the Poincaré inequality might be extended to the positive recurrent diffusion case. In particular, under the same notation we obtain the following lower bound on the Poincaré constant*

$$c_{\mathrm{P}} \ge \sup_a \inf_{x\in\mathbb{R}} V_a(x),$$

where the supremum is taken over all positive $\mathscr{C}^2$ function a on $\mathbb{R}$. Note that up to the transformation $a \to 1/a$, such a formula was already obtained by Chen and Wang in [C-W] *through their theorem 3.1, equation* (3.4)*, by using a coupling approach somewhat similar to that emphasized by Chen in the discrete case.*

Theorem 2.7 allows to derive functional inequalities more general than the Poincaré inequality. Let $\mathcal{I}$ be an open interval of $\mathbb{R}$ and for a smooth convex function $\varphi : \mathcal{I} \to \mathbb{R}$ such that $\varphi'' > 0$ and $-1/\varphi''$ is convex on $\mathcal{I}$, we define the φ-entropy of a sufficiently integrable function $f : \mathbb{N} \to \mathcal{I}$ as

$$\mathrm{Ent}_\mu^\varphi(f) = \mu\left(\varphi(f)\right) - \varphi\left(\mu(f)\right).$$

Following [Cha1], we say that the stationary distribution μ satisfies a φ-entropy inequality with constant $c > 0$ if for any $\mathcal{I}$-valued function $f \in \mathcal{D}(\mathcal{E}_\mu)$ such that $\varphi'(f) \in \mathcal{D}(\mathcal{E}_\mu)$,

$$c\,\mathrm{Ent}_\mu^\varphi(f) \le \mathcal{E}_\mu\left(f, \varphi'(f)\right). \tag{3.7}$$

See for instance [Cha2] for an investigation of the properties of φ-entropies. The φ-entropy inequality (3.7) is satisfied if and only if the following entropy dissipation of the semigroup holds: for any sufficiently integrable $\mathcal{I}$-valued function f and every $t \ge 0$,

$$\mathrm{Ent}_\mu^\varphi(P_t f) \le e^{-ct}\,\mathrm{Ent}_\mu^\varphi(f).$$

We have the following corollary of theorem 2.7.

Corollary 3.7 (Entropic inequalities and Wasserstein curvature)**.** *If the birth rate λ is non-increasing and the Wasserstein curvature σ_1 (with the constant weight $u = 1$) is positive, then the φ-entropy inequality* (3.7) *holds with constant σ_1.*

Proof. As in the proof of corollary 3.3 the assertion $\sigma_1 > 0$ entails the positive recurrence of the process. Moreover, we assume once again that the $\mathcal{I}$-valued function f has finite support. By reversibility, we have

$$\begin{aligned}\mathrm{Ent}_\mu^\varphi(f) &= \int_{\mathbb{N}} \left(\varphi(P_0 f) - \varphi(\mu(f))\right)\, d\mu \\ &= -\int_{\mathbb{N}} \int_0^\infty \frac{d}{dt}\, \varphi(P_t f)\, dt\, d\mu \\ &= -\int_0^\infty \int_{\mathbb{N}} \varphi'(P_t f)\, \mathcal{L} P_t f\, d\mu\, dt \\ &= \int_0^\infty \int_{\mathbb{N}} \lambda\, \partial P_t f\, \partial\varphi'(P_t f)\, d\mu\, dt \\ &= \int_0^\infty \int_{\mathbb{N}} \lambda\, B^\varphi\left(P_t f, \partial P_t f\right)\, d\mu\, dt,\end{aligned}$$

where B^φ is as in theorem 2.7 (the identity $\partial g\, \partial\varphi'(g) = B^\varphi(g, \partial g)$ comes from $g + \partial g = g(\cdot + 1)$). Using now theorem 2.7 together with the invariance of the measure $\lambda\mu$ for the 1-modification semigroup $(P_{1,t})_{t\geq 0}$, we obtain

$$\begin{aligned}\mathrm{Ent}_\mu^\varphi(f) &\leq \int_0^\infty \int_{\mathbb{N}} e^{-\sigma_1 t}\, \lambda\, P_{1,t} B^\varphi\left(f, \partial f\right)\, d\mu\, dt \\ &= \int_0^\infty \int_{\mathbb{N}} e^{-\sigma_1 t}\, \lambda\, B^\varphi\left(f, \partial f\right)\, d\mu\, dt \\ &= \frac{1}{\sigma_1} \int_{\mathbb{N}} \lambda\, B^\varphi\left(f, \partial f\right)\, d\mu \\ &= \frac{1}{\sigma_1}\, \mathcal{E}_\mu\left(f, \varphi'(f)\right).\end{aligned}$$

□

Remark 3.8 (Examples of entropic inequalities)**.** *The constant in the φ-entropy inequality provided by corollary 3.7 is not optimal in general (compare for instance with the Poincaré inequality of corollary 3.3 when $\varphi(r) = r^2$ with $\mathcal{I} = \mathbb{R}$). The choice $\varphi(r) = r \log r$ with $\mathcal{I} = (0, \infty)$ allows us to recover the modified* log*-Sobolev inequality of* [C-DP-P, th. 3.1]*: for any positive function $f \in \mathcal{D}(\mathcal{E}_\mu)$ such that $\log f \in \mathcal{D}(\mathcal{E}_\mu)$,*

$$\sigma_1\, \mathrm{Ent}_\mu^\varphi(f) \leq \mathcal{E}_\mu(f, \log f). \tag{3.8}$$

Note that beyond this entropic inequality, it is proved in [C-DP-P] *that the entropy is convex along the semigroup (a careful reading of the proof in* [C-DP-P] *suggests that it simply boils down to commutation and convexity of A transforms!). For the $M/M/\infty$ process, the estimate of corollary 3.7 is sharp since $\sigma_1 = \nu$ and the equality in* (3.8) *holds as $\alpha \to \infty$ for the function $x \in \mathbb{N} \mapsto e^{\alpha x}$. Note that the $M/M/1$ process and its invariant distribution, which is geometric, do not satisfy a modified* log*-Sobolev inequality. Another φ-entropy inequality of interest is that obtained when considering the convex function $\phi(r) := r^p$, $p \in (1, 2]$, with $\mathcal{I} = (0, \infty)$: for any positive function $f \in \mathcal{D}(\mathcal{E}_\mu)$ such that $f^{p-1} \in \mathcal{D}(\mathcal{E}_\mu)$,*

$$\mu(f^p) - \mu(f)^p \leq \frac{p}{\sigma_1}\, \mathcal{E}_\mu(f, f^{p-1}). \tag{3.9}$$

Such an inequality has been studied in [B-T] *in the case of Markov processes on a finite state space and also in* [Cha2] *for the $M/M/\infty$ queuing process. In particular, it can be seen as an interpolation between Poincaré and modified* log*-Sobolev inequalities.*

Under the positive recurrence assumption, theorem 2.1 implies also other type of functional inequalities such as discrete isoperimetry and transportation-information inequalities. Given a positive function u, we focus on the distance d_u constructed in section 3.1,

where we assume moreover that $\rho \in \mathcal{D}(\mathcal{E}_\mu)$, i.e. λu^2 is μ-integrable or, in other words, the u-modification process $(X_{u,t})_{t\geq 0}$ is positive recurrent. The invariant measure μ is said to satisfy a weighted isoperimetric inequality with weight u and constant $h_u > 0$ if for any absolutely continuous probability measure π with density $f \in \mathcal{D}(\mathcal{E}_\mu)$ with respect to μ,

$$h_u \, \mathcal{W}_{d_u}(\pi, \mu) \leq \int_{\mathbb{N}} \lambda \, u \, |\partial f| \, d\mu, \tag{3.10}$$

where the Wasserstein distance $\mathcal{W}_{d_u}$ is defined in (3.1) with respect to the distance d_u. The terminology of isoperimetry is employed here because it is a generalization of the classical isoperimetry, which states that the centered L^1-norm is dominated by an energy of L^1-type. Indeed, if the weight u is identically 1, then the distance d_1 between two different points is at least 1, so that (3.10) entails

$$2h_1 \int_{\mathbb{N}} |f-1| \, d\mu = h_1 \, \mathcal{W}_d(\pi, \mu) \leq h_1 \, \mathcal{W}_{d_1}(\pi, \mu) \leq \int_{\mathbb{N}} \lambda \, |\partial f| \, d\mu,$$

where d is the trivial distance 0 or 1. Note that the L^1-energy emphasized above differs from the discrete version of the diffusion case, since our discrete gradient does not derive from Γ.

On the other hand, let us introduce the transportation-information inequalities emphasized in [G-L-W-Y]. Let α be a continuous positive and increasing function on $[0, \infty)$ vanishing at 0. The invariant measure μ satisfies a transportation-information inequality with deviation function α if for any absolutely continuous probability measure π with density f with respect to μ, we have

$$\alpha \left(\mathcal{W}_{d_u}(\pi, \mu) \right) \leq \mathcal{I}(\pi, \mu), \tag{3.11}$$

where the so-called Fisher-Donsker-Varadhan information of π with respect to μ is defined as

$$\mathcal{I}(\pi, \mu) := \begin{cases} \mathcal{E}_\mu(\sqrt{f}, \sqrt{f}) & \text{if } \sqrt{f} \in \mathcal{D}(\mathcal{E}_\mu); \\ \infty & \text{otherwise.} \end{cases}$$

Note that $\mathcal{I}(\cdot, \mu)$ is nothing but the rate function governing the large deviation principle in large time of the empirical measure $L_t := t^{-1} \int_0^t \delta_{X_s} \, ds$, where δ_x is the Dirac mass at point x. In other words, the Fisher-Donsker-Varadhan information rewrites as the variational identity [Che2, th. 8.8]:

$$\mathcal{I}(\pi, \mu) = \sup_{V \in \mathcal{F}_+} \int_{\mathbb{N}} -\frac{\mathcal{L}V}{V} \, d\pi.$$

The interest of the transportation-information inequality resides in the equivalence with the following tail estimate of the empirical measure [G-L-W-Y, th. 2.4]: for any absolutely continuous probability measure π with density $f \in L^2(\mu)$ with respect to μ, and any $g \in \mathrm{Lip}_1(d_u)$,

$$\mathbb{P}_\pi \left(L_t(g) - \mu(g) > r \right) \leq \|f\|_{L^2(\mu)} \, e^{-\alpha(r)}, \quad r > 0, \quad t > 0.$$

We have the following corollary of theorem 2.1.

Corollary 3.9 (Weighted isoperimetry and transportation-information inequality)**.** *With the notations of theorem 2.1, assume that the process is positive recurrent and that the following quantity is well-defined:*

$$\kappa_u := \int_0^\infty \sup_{x \in \mathbb{N}} \mathbb{E}_x \left[\exp\left(-\int_0^t V_u(X_{u,s}) \, ds \right) \right] dt < \infty.$$

Then the weighted isoperimetric inequality (3.10) *is satisfied with constant* $h_u = 1/\kappa_u$*. If moreover there exists two constants* $\varepsilon > 0$ *and* $\theta > 1$ *such that*

$$(1+\varepsilon)\lambda_x u_x^2 + (1 + 1/\varepsilon)\nu_x u_{x-1}^2 \leq -a \left(\lambda_x(\theta - 1) + \nu_x(1/\theta - 1) \right) + b, \quad x \in \mathbb{N}, \tag{3.12}$$

where $a := a_{\varepsilon,\theta} \geq 0$ *and* $b := b_{\varepsilon,\theta} > 0$ *are two other constants depending on both* ε *and* θ*, then the transportation-information inequality* (3.11) *is satisfied with deviation function*

$$\alpha(r) := \sup_{\varepsilon>0,\theta>1} \frac{\sqrt{b^2 + 2a(r/\kappa_u)^2} - b}{2a}.$$

Remark 3.10 (The case of positive Wasserstein curvature)**.** *In particular if the Wasserstein curvature* σ_u *with respect to the distance* d_u *is positive, then the process is positive recurrent and we have*

$$\sigma_u \, \mathcal{W}_{d_u}(\pi,\mu) \leq \int_{\mathbb{N}} \lambda \, u \, |\partial f| \, d\mu \quad \textit{and} \quad \alpha\left(\mathcal{W}_{d_u}(\pi,\mu)\right) \leq \mathcal{I}(\pi,\mu),$$

with the deviation function

$$\alpha(r) := \sup_{\varepsilon>0,\theta>1} \frac{\sqrt{b^2 + 2a(r\sigma_u)^2} - b}{2a}.$$

Proof. For every $f, g \in \mathcal{D}(\mathcal{E}_\mu)$ we have, by reversibility,

$$\begin{aligned}
\mathrm{Cov}_\mu(f,g) &:= \int_{\mathbb{N}} \left(g - \int_{\mathbb{N}} g \, d\mu \right) f \, d\mu \\
&= \int_{\mathbb{N}} \left(- \int_0^\infty \mathcal{L} P_t g \, dt \right) f \, d\mu \\
&= \int_0^\infty \left(- \int_{\mathbb{N}} P_t g \, \mathcal{L} f \, d\mu \right) dt \\
&= \int_0^\infty \mathcal{E}_\mu(P_t g, f) \, dt. \qquad (3.13)
\end{aligned}$$

Now, for every probability measure $\pi \ll \mu$ with $d\pi = f d\mu$, $f \in \mathcal{D}(\mathcal{E}_\mu)$, we get, using (3.13),

$$\begin{aligned}
\mathcal{W}_{d_u}(\pi,\mu) &= \sup_{g \in \mathrm{Lip}_1(d_u)} \mathrm{Cov}_\mu(f,g) \\
&= \sup_{g \in \mathrm{Lip}_1(d_u)} \int_0^\infty \mathcal{E}_\mu(P_t g, f) \, dt \\
&= \sup_{g \in \mathrm{Lip}_1(d_u)} \int_0^\infty \int_{\mathbb{N}} \lambda \, u \, \partial f \; \partial_u P_t g \, d\mu \, dt \\
&= \int_0^\infty \int_{\mathbb{N}} \lambda \, u \, |\partial f| \; \partial_u P_t \rho \, d\mu \, dt \\
&\leq \int_0^\infty \sup_{x \in \mathbb{N}} \mathbb{E}_x \left[\exp\left(- \int_0^t V_u(X_{u,s}) \, ds \right) \right] dt \int_{\mathbb{N}} \lambda \, u \, |\partial f| \, d\mu,
\end{aligned}$$

where in the last inequality we used theorem 2.1. This concludes the proof of the weighted isoperimetric inequality.

Using now Cauchy-Schwarz inequality, reversibility and then (3.12) with $V_\theta(x) := \theta^x$, $x \in \mathbb{N}$,

$$\begin{aligned}
\mathcal{W}_{d_u}(\pi,\mu) &\leq \kappa_u \sqrt{\mathcal{I}(\pi,\mu)} \sqrt{\int_{\mathbb{N}} \lambda \, u^2 \left(\sqrt{f(\cdot+1)} + \sqrt{f} \right)^2 d\mu} \\
&\leq \kappa_u \sqrt{\mathcal{I}(\pi,\mu)} \sqrt{\int_{\mathbb{N}} \left((1+\varepsilon)\lambda u^2 + (1+1/\varepsilon)\nu u_{\cdot-1}^2 \right) f \, d\mu} \\
&\leq \kappa_u \sqrt{\mathcal{I}(\pi,\mu)} \sqrt{\int_{\mathbb{N}} \left(-a \, \frac{\mathcal{L} V_\theta}{V_\theta} + b \right) f \, d\mu} \\
&\leq \kappa_u \sqrt{\mathcal{I}(\pi,\mu)} \sqrt{a \mathcal{I}(\pi,\mu) + b},
\end{aligned}$$

from which the desired transportation-information inequality holds. □

Remark 3.11 ($M/M/\infty$ and $M/M/1$ revisited)**.** *Corollary 3.9 exhibits optimal functional inequalities, at least in the $M/M/\infty$ case and its stationary distribution, the Poisson measure of mean λ/ν. Choosing the weight $u = 1$, we obtain the optimal constant $\hbar_1 = \nu$ in the isoperimetric inequality. Indeed, corollary 3.9 entails $\hbar_1 \geq \nu$, whereas the other inequality is obtained by choosing π a Poisson measure of different parameter. For the transportation-information inequality, we recover theorem 2.1 in* [M-W-W] *since the choice of $a := \theta(1 + 1/\varepsilon)/(\theta - 1)$ and $b := \lambda(1 + \varepsilon + (1 + 1/\varepsilon)\theta)$ allows us to obtain the deviation function $\alpha(r) := \lambda(\sqrt{1 + \nu r/\lambda} - 1)^2$, $r > 0$. Note that it is optimal in view of example 4.5 in* [G-G-W]*: for any absolutely continuous probability measure π with square-integrable density with respect to μ,*

$$\lim_{t\to\infty} \frac{1}{t} \log \mathbb{P}_\pi \left(\frac{1}{t} \int_0^t X_s \, ds - \frac{\lambda}{\nu} > r \right) = -\lambda \left(\sqrt{1 + \frac{\nu r}{\lambda}} - 1 \right)^2, \quad r > 0.$$

For the $M/M/1$ process, we have the following inequalities for the optimal isoperimetric constant $\hbar_u$, with $u_x = (\nu/\lambda)^{x/2}$ (a quantity that will appear again in section 3.3):

$$(\sqrt{\lambda} - \sqrt{\nu})^2 \leq \hbar_u \leq (\sqrt{\nu} - \sqrt{\lambda})\sqrt{\nu}.$$

To get the second inequality, we choose the density $f = (\nu/\lambda)(1 - 1_{\{0\}})$ and the 1-Lipschitz test function $g = \rho$. In particular as the ratio λ/ν is small, we obtain $\hbar_u \approx \nu$. However, we ignore if such a process satisfies a transportation-information inequality.

3.3. **Hitting time of the origin by the $M/M/1$ process.** Recall that we consider the ergodic $M/M/1$ process ($\lambda < \nu$) for which the stationary distribution is geometric of parameter λ/ν. Since the process behaves as a random walk outside 0, the ergodic property relies essentially on its behavior at point 0. Using the notation of theorem 2.1, the intertwining relation (2.2) applied with a positive function u entails the identity

$$\partial_u P_t f(x) = \mathbb{E}_x \left[\partial_u f(X_t) \exp\left(- \int_0^t V_u(X_{u,s}) \, ds \right) \right]$$

where the potential is given for every $x \in \mathbb{N}$ by

$$V_u(x) := \nu - \frac{u_{x-1}}{u_x} \nu \mathbf{1}_{\{x \neq 0\}} + \lambda - \frac{u_{x+1}}{u_x} \lambda.$$

Following Robert [R], the process $(X_t^y)_{t\geq 0}$ is the solution of the stochastic differential equation

$$X_0^y = y \quad \text{and} \quad dX_t^y = dN_t^{(\lambda)} - \mathbf{1}_{\{X_{t-}^y > 0\}} \, dN_t^{(\nu)}, \quad t > 0, \tag{3.14}$$

where $(N_t^{(\lambda)})_{t\geq 0}$ and $(N_t^{(\nu)})_{t\geq 0}$ are two independent Poisson processes with parameter λ and ν, respectively. Since the process is assumed to be positive recurrent, the hitting time of 0,

$$T_0^y := \inf\{t > 0 : X_t^y = 0\}$$

is finite almost surely. We have the following corollary of theorem 2.1.

Corollary 3.12 (Hitting time of the origin for the ergodic $M/M/1$ process)**.** *Given $x \in \mathbb{N}$, consider a positive recurrent $M/M/1$ process $(X_t^{x+1})_{t\geq 0}$ starting at point $x + 1$, and denote $(X_{u,t}^x)_{t\geq 0}$ its u-modification process starting at point x, where*

$$u_x := \left(\frac{\nu}{\lambda} \right)^{\frac{x}{2}} \geq 1.$$

Then we have the following tail estimate: for any $t \geq 0$,

$$\mathbb{P}(T_0^{x+1} > t) = u_x\, e^{-t\left(\sqrt{\lambda}-\sqrt{\nu}\right)^2}\, \mathbb{E}\left[\frac{1}{u(X_{u,t}^x)}\, \exp\left(-\sqrt{\lambda\nu}\int_0^t \mathbf{1}_{\{0\}}(X_{u,s}^x)\, ds\right)\right]$$
$$\leq u_x\, e^{-t\left(\sqrt{\lambda}-\sqrt{\nu}\right)^2}.$$

Proof. Let us use a coupling argument. Let $(X_t^x)_{t\geq 0}$ be a copy of $(X_t^{x+1})_{t\geq 0}$, starting at point x. We assume that it constructed with respect to the same driving Poisson processes $(N_t^{(\lambda)})_{t\geq 0}$ and $(N_t^{(\nu)})_{t\geq 0}$ as the process $(X_t^{x+1})_{t\geq 0}$. Hence the stochastic differential equation (3.14) satisfied by the two coupling processes entails that the difference between $(X_t^{x+1})_{t\geq 0}$ and $(X_t^x)_{t\geq 0}$ remains constant, equal to 1, until time T_0^{x+1}, the first hitting time of the origin by $(X_t^{x+1})_{t\geq 0}$. After time T_0^{x+1}, the processes are identically the same, so that the following identity holds:

$$X_t^{x+1} = X_t^x + \mathbf{1}_{\{T_0^{x+1}>t\}}, \quad t \geq 0.$$

Since the original process is assumed to be positive recurrent, the coupling is successful, i.e. the coupling time is finite almost surely. Therefore we have for any function $f \in \mathrm{Lip}(d_1)$, where d_1 is the distance $d_1(x,y) = |x-y|$,

$$\partial P_t f(x) = P_t f(x+1) - P_t f(x) = \mathbb{E}\left[f(X_t^{x+1}) - f(X_t^x)\right] = \mathbb{E}\left[\partial f(X_t^x)\, \mathbf{1}_{\{T_0^{x+1}>t\}}\right]$$

so that if we denote the function $\rho(x) = x$, we obtain

$$\mathbb{P}(T_0^{x+1} > t) = \partial P_t \rho(x) = u_x\, \partial_u P_t \rho(x).$$

Using now (2.2) with the function u, we get

$$\mathbb{P}(T_0^{x+1} > t) = u_x\, \mathbb{E}\left[\frac{1}{u(X_{u,t}^x)}\, \exp\left(-\int_0^t V_u(X_{u,s}^x)\, ds\right)\right],$$

where $V_u := (\sqrt{\lambda}-\sqrt{\nu})^2 + \sqrt{\lambda\nu}\, \mathbf{1}_{\{0\}}$. □

Remark 3.13 (Sharpness)**.** *Using a completely different approach, Van Doorn established in* [VD]*, through his theorem 4.2 together with his example 5, the following asymptotics*

$$\lim_{t\to\infty} \frac{1}{t}\, \log\, \mathbb{P}(T_0^{x+1} > t) = -(\sqrt{\lambda}-\sqrt{\nu})^2, \quad x \in \mathbb{N}.$$

Hence one deduces that the exponential decay in the result of corollary 3.12 is sharp. On the other hand, proposition 5.4 in [R] *states that T_0^{x+1} has exponential moment bounded as follows:*

$$\mathbb{E}\left[e^{(\sqrt{\lambda}-\sqrt{\nu})^2 T_0^{x+1}}\right] \leq \left(\frac{\nu}{\lambda}\right)^{(x+1)/2},$$

so that Chebyshev's inequality yields a tail estimate somewhat similar to ours - although with a worst constant depending on the initial point $x+1$.

Remark 3.14 (Other approach)**.** *The proof of corollary 3.12 suggests also a martingale approach. First, note that we have the identity*

$$-\nu\, \mathbf{1}_{\{0\}} = -\frac{\mathcal{L}u}{u} - V_u$$

which entails as in the previous proof and since $u \geq 1$, the following computations:

$$\begin{aligned}\mathbb{P}(T_0^{x+1} > t) &= \partial P_t \rho(x) \\ &= \mathbb{E}\left[\exp\left(-\int_0^t \nu\, \mathbf{1}_{\{0\}}(X_s^x)\, ds\right)\right] \\ &\leq \mathbb{E}\left[u(X_t^x)\, \exp\left(-\int_0^t \left(\frac{\mathcal{L}u}{u} + V_u\right)(X_s^x)\, ds\right)\right] \\ &\leq u_x\, e^{-t\,(\sqrt{\lambda}-\sqrt{\nu})^2},\end{aligned}$$

since the process $(M_t^u)_{t\geq 0}$ given by

$$M_t^u := u(X_t^x)\, \exp\left(-\int_0^t \frac{\mathcal{L}u}{u}(X_s^x)\, ds\right), \quad t \geq 0,$$

is a supermartingale. Indeed, denoting

$$Z_t^u := \exp\left(-\int_0^t \frac{\mathcal{L}u}{u}(X_s^x)\, ds\right),$$

we have by Ito's formula:

$$\begin{aligned}dM_t^u &= Z_t^u du(X_t^x) + u(X_t^x)\, dZ_t^u \\ &= Z_t^u(dM_t + \mathcal{L}u(X_t^x)dt) - u(X_t^x)\frac{\mathcal{L}u}{u}(X_t^x)\, Z_t^u dt \\ &= Z_t^u dM_t,\end{aligned}$$

where $(M_t)_{t\geq 0}$ is a local martingale. Therefore, the process $(M_t^u)_{t\geq 0}$ is a positive local martingale and thus a supermartingale.

3.4. **Convex domination of birth-death processes.** Let $(X_t^x)_{t\geq 0}$ be the $M/M/\infty$ process starting from $x \in \mathbb{N}$. The Mehler-type formula (1.2) states that the random variable X_t^x has the same distribution as the independent sum of the variable X_t^0, which follows the Poisson distribution of parameter $(\lambda/\nu)(1 - e^{-\nu t})$, and a binomial random variable $B_t^{(x)}$ of parameters $(x, e^{-\nu t})$. By convention, $B_t^{(0)}$ is assumed to be 0. Hence we have for any non-negative function f and any $x \in \mathbb{N}$,

$$\mathbb{E}\left[f(X_t^x)\right] = \mathbb{E}[f(X_t^0 + B_t^{(x)})], \quad t \geq 0. \tag{3.15}$$

Such an identity can be provided by using the commutation relation (1.4). Indeed we have

$$\mathbb{E}\left[f(X_t^{x+1})\right] = (1 - e^{-\nu t})\, \mathbb{E}\left[f(X_t^x)\right] + e^{-\nu t}\, \mathbb{E}[f(X_t^x + 1)],$$

so that a recursive argument on the initial state provides the required result. An interesting consequence of (3.15) appears in terms of concentration properties. For instance a straightforward computation entails that for any $\theta \geq 0$, we get the following inequality on the Laplace transforms

$$\mathbb{E}\left[e^{\theta X_t^x}\right] \leq \mathbb{E}\left[e^{\theta N_t^x}\right],$$

where N_t^x is a Poisson random variable with the same mean as X_t^x. Therefore, using the exponential Chebyshev inequality entails an upper bound on the tail of the centered random variable $X_t^x - \mathbb{E}[X_t^x]$, which is sharp as $t \to \infty$ (recall that the stationary distribution is Poisson with parameter λ/ν).

Actually, one may ask if for a more general birth-death process, the intertwining relation of type (2.2) may imply a relation similar to (3.15). This leads to the notion of stochastic ordering.

Following the presentation enlighten by Stoyan in [S], let us start with the classical notion of stochastic ordering for integer-valued random variables. We say that X is stochastically smaller than Y, and we note $X \leq_d Y$, if for any function $f \in \mathcal{F}_d$,

$$\mathbb{E}[f(X)] \leq \mathbb{E}[f(Y)].$$

Such a relation, as the convex domination introduced below, is a partial ordering on the set of distribution functions. The interesting feature of this stochastic ordering resides in its characterization in terms of coupling: we have $X \leq_d Y$ if and only if there exist random variables X_1 and Y_1, both defined on the same probability space and with the same distribution as X and Y respectively, such that $\mathbb{P}(X_1 \leq X_2) = 1$. Moreover, it is equivalent to the following comparison between tails: we have $X \leq_d Y$ if and only $\mathbb{P}(X \geq x) \leq \mathbb{P}(Y \geq x)$ for any $x \in \mathbb{R}$. In other words, the random variable X takes small values with a higher probability than Y does.

Another stochastic ordering of interest is the convex ordering, or convex domination. Denote $\mathcal{F}_c$ the subset of $\mathcal{F}_d$ consisting of non-negative non-decreasing convex functions, where in our discrete setting the convexity of a function $f : \mathbb{N} \to \mathbb{R}$ is understood as $\partial^2 f \geq 0$. We say that X is convex dominated by Y, and we note $X \leq_{\mathrm{c}} Y$, if for any function $f \in \mathcal{F}_c$,

$$\mathbb{E}[f(X)] \leq \mathbb{E}[f(Y)].$$

It is known to be equivalent to the inequality

$$\mathbb{E}\left[(X-x)^+\right] \leq \mathbb{E}\left[(Y-x)^+\right], \quad x \in \mathbb{R},$$

where $a^+ := \max\{a, 0\}$. Typically, one may deduce from the convex domination concentration properties like a comparison of moments or Laplace transforms as in the $M/M/\infty$ case above. Moreover, this refined ordering might appear for instance when using de-la-Vallée-Poussin's lemma about uniform integrability of a family of random variables. However, in contrast to the $\leq_d$ ordering, the authors ignore if there exists a genuine interpretation of the convex domination in terms of coupling.

Coming back to our birth-death framework, we observe that if we want to use the intertwining relation (2.2) of theorem 2.1 in order to obtain stochastic domination, then a first difficulty arises. Indeed, another birth-death process appears in the right-hand-side of (2.2), namely the u-modification of the original process. Therefore, let us provide first a lemma which allows us to compare two birth-death processes with respect to the $\leq_d$ ordering. Although the result below is somewhat obvious from the point of view of coupling, we give an alternative proof based on the interpolation method emphasized in the proof of theorem 2.1. See also [S, prop. 4.2.10].

Lemma 3.15 (Stochastic comparison of birth-death processes)**.** *Let $(X_t^x)_{t\geq 0}$ and $(\tilde{X}_t^x)_{t\geq 0}$ be two birth-death processes both starting from $x \in \mathbb{N}$. Denoting respectively λ, ν and $\tilde{\lambda}, \tilde{\nu}$ the transition rates of the associated generators $\mathcal{L}$ and $\tilde{\mathcal{L}}$, we assume that they satisfy the following assumption:*

$$\tilde{\lambda} \leq \lambda \quad \text{and} \quad \tilde{\nu} \geq \nu$$

Then for every $t \geq 0$, the random variable $\tilde{X}_t^x$ is stochastically smaller than X_t^x. In other words, we have $\tilde{X}_t^x \leq_d X_t^x$.

Proof. Let $g \in \mathcal{F}_d$ and define the function $s \in [0, t] \mapsto J(s) := \tilde{P}_s P_{t-s} g$ where $(P_t)_{t\geq 0}$ and $(\tilde{P}_t)_{t\geq 0}$ are the semigroups of $(X_t^x)_{t\geq 0}$ and $(\tilde{X}_t^x)_{t\geq 0}$ respectively. By differentiation, we have

$$J'(s) = \tilde{P}_s\left(\tilde{\mathcal{L}} P_{t-s} g - \mathcal{L} P_{t-s} g\right) = \tilde{P}_s\left((\tilde{\lambda} - \lambda)\, \partial P_{t-s} g + (\tilde{\nu} - \nu)\, \partial^* P_{t-s} g\right),$$

which is non-positive since the semigroup $(P_t)_{t\geq 0}$ satisfies the propagation of monotonicity, cf. remark 2.4. Hence the function J is non-increasing and the desired result holds. $\square$

Now we are able to state the following corollary of theorem 2.1, which states a new convex domination involving decoupled random variables in the right-hand-side. However, despite some particular cases like the $M/M/1$ case for which the convenient coupling appearing in the proof of corollary 3.12 allows us to extend the next result to the $\leq_d$ ordering, we ignore if it can be done in full generality.

Corollary 3.16 (Convex domination)**.** *Denote $(X_t^y)_{t\geq 0}$ a birth-death process starting at some point $y \in \mathbb{N}$. We assume that the birth rate λ is non-increasing and that there exists $\kappa \geq 0$ such that*

$$\partial(\nu - \lambda) \geq \kappa.$$

Then for any $t \geq 0$ and any $x \in \mathbb{N}$, the random variable X_t^{x+1} is convex dominated by the independent sum of X_t^x and a Bernoulli random variable Y_t of parameter $e^{-\kappa t} \in (0, 1]$. In other words, we have

$$X_t^{x+1} \leq_{\mathrm{c}} X_t^x + Y_t.$$

Proof. We have to show that for any function $f \in \mathcal{F}_c$,

$$\mathbb{E}\Big[f(X_t^{x+1})\Big] \leq \mathbb{E}[f(X_t^x + Y_t)]. \tag{3.16}$$

Using the intertwining relation (2.2) of theorem 2.1, we have since f is non-decreasing:

$$\begin{aligned}
\mathbb{E}\Big[f(X_t^{x+1})\Big] &\leq \mathbb{E}[f(X_t^x)] + e^{-\kappa t}\,\mathbb{E}\Big[\partial f(X_{1,t}^x)\Big] \\
&\leq \mathbb{E}[f(X_t^x)] + e^{-\kappa t}\,\mathbb{E}[\partial f(X_t^x)] \\
&= (1 - e^{-\kappa t})\,\mathbb{E}[f(X_t^x)] + e^{-\kappa t}\,\mathbb{E}[f(X_t^x + 1)] \\
&= \mathbb{E}[f(X_t^x + Y_t)],
\end{aligned}$$

where to obtain the second inequality we used lemma 3.15 with the 1-modification process $(X_{1,t}^x)_{t\geq 0}$ playing the role of $(\tilde{X}_t^x)_{t\geq 0}$ since ∂f is non-decreasing (recall that $f \in \mathcal{F}_c$). $\square$

Remark 3.17 (More on convex domination)**.** *By an easy recursive argument one obtains from the latter result the following convex domination:*

$$X_t^x \leq_{\mathrm{c}} X_t^0 + B_t^{(x)},$$

where $B_t^{(x)}$ is a binomial random variable of parameters $(x, e^{-\kappa t})$, independent from X_t^0, as in the case of the $M/M/\infty$ queuing process.

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