Displacement convexity for the entropy in semi-discrete non-linear Fokker–Planck equations†

JOSÉ A. CARRILLO1, ANSGAR JÜNGEL2 and MATHEUS C. SANTOS3

1Department of Mathematics, Imperial College London, London SW7 2AZ, UK
e-mail: carrillo@imperial.ac.uk
2Institute for Analysis and Scientific Computing, Vienna University of Technology, Wiedner Hauptstraße 8-10, 1040 Wien, Austria
email: juengel@tuwien.ac.at
3Departamento de Matemática – IMECC, Universidade Estadual de Campinas, Campinas-SP, Brazil
email: matheus.santos@ufrgs.com

(Received 28 May 2017; revised 13 December 2017; accepted 14 December 2017; first published online 10 January 2018)

The displacement $\lambda$-convexity of a non-standard entropy with respect to a non-local transportation metric in finite state spaces is shown using a gradient flow approach. The constant $\lambda$ is computed explicitly in terms of a priori estimates of the solution to a finite-difference approximation of a non-linear Fokker–Planck equation. The key idea is to employ a new mean function, which defines the Onsager operator in the gradient flow formulation.

Key words: Entropy, displacement convexity, logarithmic mean, finite differences, fast-diffusion equation

2000 Mathematics Subject Classification. 60J27, 53C21, 65M20

1 Introduction

Displacement convexity, which was introduced by McCann [20], describes the geodesic convexity of functionals on the space of probability measures endowed with a transportation metric. Geodesic convexity has important consequences for the existence and uniqueness of gradient flows in the space of probability measures [1, 6, 22]. It may also provide quantitative contraction estimates between solutions of the gradient flows [5] and exponential decay estimates [1]. Displacement $\lambda$-convexity of the entropy is equivalent to a lower bound on the Ricci curvature $\text{Ric}_M$ of the Riemannian manifold $M$, i.e., $\text{Ric}_M \geq \lambda$ [17, 23]. Furthermore, it leads to inequalities in convex geometry and probability theory, such as the Brunn–Minkowski, Talagrand and log-Sobolev inequalities [25].

† The first author was partially supported by the Royal Society via a Wolfson Research Merit Award and the EPSRC Grant EP/P031587/1. The second author acknowledges partial support from the Austrian Science Fund (FWF), Grants P22108, P24304, F65 and W1245. The last author acknowledges the support from the São Paulo Research Foundation (FAPESP), Grant 2015/20962-7.
We are interested in the question to what extent the concept of displacement convexity can be extended to discrete settings, like numerical discretisation schemes of gradient flows. As one step in this direction, we show in this paper that a certain entropy functional, related to the finite-difference approximation of non-linear Fokker–Planck equations, is displacement convex. Before making this statement more precise, let us review the state of the art of the literature.

The study of discrete gradient flows and related topics is very recent. First, results were concerned with Ricci curvature bounds in discrete settings [3]. Markov processes and Fokker–Planck equations on finite graphs were investigated by Chow et al. in [7]. Maas [18] and Mielke [21] introduced non-local transportation distances on probability spaces such that continuous-time Markov chains can be formulated as gradient flows of the entropy, and they explored geodesic convexity properties of the functionals. The concept of displacement convexity was used by Gozlan et al. [12] to derive HWI inequality (which interpolates the relative entropy H, the Wasserstein distance W and the Fisher information I) and log-Sobolev inequalities on (complete) graphs. Talagrand’s inequality was studied in discrete spaces by Sammer and Tetali [24].

Only few results can be found in the literature on convexity properties of functionals for discretisations of partial differential equations. Exponential decay rates for time-continuous Markov chains were derived by Caputo et al. [4]. This result was also obtained for reversible Markov chains as a consequence of the displacement convexity of the Shannon entropy as first investigated by Mielke [21] and applied to discretisations of one-dimensional linear Fokker-Planck equations (also see the presentation in [14, Section 5.2]). While the proof of Caputo et al. [4] is based on the Bochner–Bakry–Emery method, Mielke [21] employed a gradient flow approach together with matrix estimates. The non-local transportation metric, needed for the definition of displacement convexity, is induced by the logarithmic mean:

\[ \Lambda(s, t) = \frac{s - t}{\log s - \log t} \quad \text{for } s \neq t, \quad \Lambda(s, s) = s, \]

which has some remarkable properties (proved in [21] and summarized in Lemma 7 below). The same mean function has been used for finite volume discretisations of drift-diffusion equations [2, equation (28)]. The approach of [4] (and [11]) was extended to general convex entropy densities \( f(s) \) in [15] using the mean function:

\[ A^f(s, t) = \frac{s - t}{f'(s) - f'(t)} \quad \text{for } s \neq t, \quad A^f(s, s) = \frac{1}{f''(s)}, \tag{1.1} \]

which becomes the logarithmic mean for \( f(s) = s \log s - 1 \).

Concerning non-linear equations, we are aware only of two results. Erbar and Maas [10] showed that a discrete one-dimensional porous-medium equation is a gradient flow of the Rényi entropy function \( f(s) = s^\alpha \) with respect to a suitable non-local transportation metric induced by the mean function:

\[ A^\alpha(s, t) = \frac{\alpha - 1}{\alpha} \frac{s^\alpha - t^\alpha}{s^{\alpha-1} - t^{\alpha-1}} \quad \text{for } s \neq t, \quad A^\alpha(s, s) = s. \]

However, the Rényi entropy fails to be convex along geodesics with respect to this transportation metric [10]. A weaker notion than geodesic convexity (called convex
entropy decay), which is strongly related to the Bakry–Emery method, was introduced by Maas and Matthes [19] to prove exponential decay rates for finite-volume discretisations of the quantum drift-diffusion equation. Its gradient flow formulation is based on the Fisher information and the logarithmic mean.

In this paper, we propose a new mean function by composing the logarithmic mean with a non-linear function (coming from the diffusivity), which is suitable for finite-difference discretisations of the non-linear Fokker–Planck equation

$$\partial_t \rho = \partial_x \left( \partial_x \phi(\rho) + \phi(\rho) \partial_x V \right), \quad x \in (0, 1), \ t > 0,$$

supplemented with no-flux boundary conditions and an initial condition. Equations with non-linear mobility were already treated under the point of view of optimal transport in [16], and the displacement convexity of equations related to (1.2) was analysed in [6]. Here, \( \phi : [0, \infty) \rightarrow [0, \infty) \) is a continuous function, e.g., \( \phi(\rho) = \rho^\alpha \) with \( \alpha > 0 \), and \( V(x) \) is a quadratic confinement potential \( V(x) = \gamma |x|^2 / 2 \) with \( \gamma > 0 \). A computation shows that the entropy

$$F_c(\rho) = \int_0^1 \left( f(\rho) + \rho V(x) \right) dx,$$

where \( f'(s) = \log \phi(s) \), is non-increasing along (smooth) solutions to (1.2). Our aim is to analyse the displacement convexity of a discrete version of the entropy \( F_c \) along semi-discrete solutions associated to (1.2).

For the discretisation of (1.2), let \( n \in \mathbb{N} \), \( h = 1/n > 0 \), and \( x_i = ih, \ i = 0, \ldots, n \). Let \( \rho_i(t) \) approximate the solution \( \rho(x_i, t) \) and \( w_i \) approximate the function \( w(x_i) = e^{-V(x_i)} \). Writing (1.2) in the form

$$\partial_t \rho = \text{div} \left( \phi(\rho) \nabla \log \frac{\phi(\rho)}{w} \right),$$

a corresponding finite-difference scheme reads as

$$\partial_t \rho_i = \frac{\kappa_i A_i}{h^2} \left( \log \frac{\phi(\rho_{i+1})}{w_{i+1}} - \log \frac{\phi(\rho_i)}{w_i} \right) - \frac{\kappa_{i-1} A_{i-1}}{h^2} \left( \log \frac{\phi(\rho_i)}{w_i} - \log \frac{\phi(\rho_{i-1})}{w_{i-1}} \right), \quad (1.3)$$

where \( h > 0 \) is the space size and \( \kappa_i A_i \) is an approximation of \( \phi(\rho) \) in \([x_i, x_{i+1}]\). To simplify the notation, let us write \( u_i = \phi(\rho_i)/w_i \), for \( i = 0, \ldots, n \). Our idea is to employ the modified logarithmic mean

$$A_i = \frac{u_i - u_{i+1}}{\log u_i - \log u_{i+1}}, \quad (1.4)$$

and to set, as in [21], \( \kappa_i = \sqrt{w_i w_{i+1}} \). Since \( A_i \) approximates \( u_i \), it follows that \( \kappa_i A_i \) approximates \( \sqrt{w_{i+1}/w_i} \phi(\rho_i) \). Observe that with this choice, the numerical scheme reduces to

$$\partial_t \rho_i = \frac{\kappa_i}{h^2} (u_{i+1} - u_i) - \frac{\kappa_{i-1}}{h^2} (u_i - u_{i-1}),$$

which approximates (1.2) written in the form \( \partial_t \rho = \partial_x (w \partial_x (\phi(\rho)/w)) \).
The main result of the paper is as follows. If \( \phi \) is invertible and \( \phi' \circ \phi^{-1} \) is non-increasing (an example is \( \phi(s) = s^x \) with \( 0 < x \leq 1 \)), then the discrete entropy

\[
\mathcal{F}(\rho) = \sum_{i=0}^{n} \left( f(\rho_i) + \frac{\gamma}{2} \rho_i^2 \right), \quad \text{where } f'(s) = \log \phi(s),
\]

is displacement \( \lambda_h \)-convex with respect to the non-local transportation metric induced by (1.4), where \( \lambda_h = \gamma \left( \frac{2}{\gamma h^2} (1 - e^{-\gamma h^2/2}) \min_{i=0,\ldots,n} \phi'(\rho_i) - 2 \cosh(\gamma h) \max_{i=0,\ldots,n} |\nabla_h \phi'(\rho_i)| \right) \in \mathbb{R} \), and \( \nabla_h \phi'(\rho_i) = h^{-1}(\phi'(\rho_{i+1}) - \phi'(\rho_i)) \); see Theorem 3. Notice that \( \gamma \) is the convexity constant of the quadratic potential \( V(x) \) and that \( \lambda_h = 0 \) for \( \gamma = 0 \).

Our result is consistent with that one in [21]: If \( \phi(s) = s \) is linear (and \( V \neq 0 \)), \( \lambda_h \to \gamma \) as \( h \to 0 \), and the constant is asymptotically sharp. When \( \gamma = 0 \), our main result shows that \( \mathcal{F}(\rho) \) is displacement convex.

For \( \gamma > 0 \), if the minimum of \( \phi'(\rho_i) \) is positive and the maximum of \( |\nabla_h \phi'(\rho_i)| \) is sufficiently small, then \( \lambda_h > 0 \). We expect that exponential convergence to the steady state holds for sufficiently small \( h > 0 \), but we are unable to prove these \( a \ priori \) estimates for our numerical scheme in this whole generality. Such bounds in terms of the initial data can be shown for \( V = 0 \) and for small initial data depending on the mesh size \( h \); see Corollary 1. This is an indication that such \( a \ priori \) estimates might hold true for \( \gamma > 0 \).

The main motivation of this work is to find a family of non-linear drift-diffusion equations for which the strategy developed in [21] can be carried over. As a byproduct, we obtain semi-discrete finite difference schemes for equation (1.2) enjoying mass conservation, positivity preservation and the natural entropy dissipation property, i.e., \( \mathcal{F}(\rho) \) non-increasing.

The paper is organized as follows. In Section 2, we introduce the mathematical setting and give the definition of displacement \( \lambda \)-convexity. We show that displacement \( \lambda \)-convexity follows if a certain matrix is positive semi-definite, slightly generalising Proposition 2.1 in [21]. As a warm-up, we consider in Section 3 the semi-discrete heat equation and prove that the entropy \( \mathcal{F}(\rho) = \sum_{i=0}^{n} f(\rho_i) \) is displacement convex if \( f(s) = s(\log s - 1) \) or \( f(s) = s^x \) for \( 1 < x \leq 2 \); see Theorem 2. This result is a reformulation of Theorem 5 in [15], but our proof is very simple. Section 4 is concerned with the proof of displacement \( \lambda \)-convexity of (1.5) and contains our main result. Some properties of mean functions are recalled in Appendix A, and \( a \ priori \) estimates of solutions to (1.3) with \( V = 0 \) and small initial data depending on the small size are proved in Appendix B.

### 2 Displacement convexity

In this section, we specify our setting and give the definition of displacement convexity. Let \( n \in \mathbb{N} \) and introduce the finite state space:

\[
X_n = \left\{ \rho = (\rho_0, \ldots, \rho_n) \in \mathbb{R}^{n+1} : \rho_0, \ldots, \rho_n > 0, \sum_{i=0}^{n} \rho_i = 1 \right\}.
\]
Displacement convexity

The closure of \( X_n \) can be identified with the space of probability measures on a \((n + 1)\)-point set. We restrict our attention to \( X_n \) in order to have the entropy dissipation term \( D\mathcal{F}(\rho) \) well defined independently of the assumptions on \( \phi \) at the origin. We will denote by \( \langle \cdot , \cdot \rangle \) the Euclidean inner product in \( \mathbb{R}^{n+1} \). Let a matrix \( Q = (Q_{ij}) \in \mathbb{R}^{(n+1)\times(n+1)} \) be given such that

\[
Q_{ij} \geq 0 \text{ for } i \neq j, \quad \sum_{i=0}^{n} Q_{ij} = 0 \text{ for } j = 1, \ldots, n.
\]

The value \( Q_{ij} \) is the rate of a particle moving from state \( j \) to \( i \). We assume that there exists a unique vector \( w \in X_n \) such that the detailed balance condition

\[
Q_{ij} w_j = Q_{ji} w_i \quad \text{for all } i, j = 0, \ldots, n
\]

is satisfied. Summing this condition for fixed \( i \) over \( j = 0, \ldots, n \), we see that \( Qw = 0 \). Note that in Markov chain theory, the detailed balance condition is usually formulated for the transposed matrix \( Q^\top \).

Our aim is to show convexity properties of the entropy along solutions \( t \mapsto \rho(t) \) to the system of ordinary differential equations of the type

\[
\partial_t \rho = Q\phi(\rho), \quad t > 0,
\]

where \( \phi \) is some smooth function. This equation can be formulated as a gradient flow. Indeed, given a (smooth) function \( f : [0, \infty) \to \mathbb{R} \), we define the entropy \( \mathcal{F} : X_n \to \mathbb{R} \),

\[
\mathcal{F}(\rho) = \sum_{i=0}^{n} f_i(\rho_i), \quad \text{where } f_i'(s) = f'(\phi(w_i/s)),
\]

and the Onsager operator \( K : X_n \to \mathbb{R}^{(n+1)\times(n+1)} \),

\[
K(\rho) = \frac{1}{2} \sum_{i,j=0}^{n} Q_{ij} w_j A f' \left( \frac{\phi(\rho_i)}{w_i}, \frac{\phi(\rho_j)}{w_j} \right) (e_i - e_j) \otimes (e_i - e_j),
\]

where \( e_i = (\delta_{i0}, \ldots, \delta_{in})^\top \in \mathbb{R}^{n+1} \) is the \( i \)th unit vector and \( \otimes \) is the tensor product. By detailed balance and \( Q_{ij} w_j \geq 0 \) for \( i \neq j \), it follows that \( K(\rho) \) is symmetric and positive semi-definite. With these definitions, we can formulate (2.1) as a gradient system in the sense that it can be rewritten as

\[
\partial_t \rho = -K(\rho)D\mathcal{F}(\rho),
\]

where \( D\mathcal{F}(\rho) = (f_0'(\rho_0), \ldots, f_n'(\rho_n)) \).

The space \( X_n \) is endowed with the non-local transportation distance

\[
\mathcal{W}(\rho_0, \rho_1)^2 = \inf_{(\rho, \psi) \in E(\rho_0, \rho_1)} \int_0^1 \langle K(\rho(t))\psi(t), \psi(t) \rangle dt,
\]

where \( E(\rho_0, \rho_1) \) is the set of pairs \( (\rho(t), \psi(t)), t \in [0, 1] \), such that

\[
\rho \in C^1([0, 1]; X_n), \quad \psi : [0, 1] \to \mathbb{R}^{n+1} \text{ is measurable},
\]

for all \( i = 0, \ldots, n \), \( t \in [0, 1] : \partial_t \rho(t) = K(\rho)\psi(t), \quad \rho(0) = \rho_0, \quad \rho(1) = \rho_1. \)
It is well known that the function $W$ is a pseudo-metric on $X_n$ (the space of probability measures on a $n+1$-point set) [18, Theorem 1.1] and the pair $(X_n, W)$ defines a geodesic space [10, Proposition 2.3], i.e., for all $\rho_0, \rho_1 \in X_n$, there exists at least one curve $\rho : [0,1] \rightarrow X_n$, $t \mapsto \rho(t)$, such that $\rho(0) = \rho_0, \rho(1) = \rho_1$, and $W(\rho(s), \rho(t)) = |s-t|W(\rho_0, \rho_1)$ for all $s, t \in [0,1]$. Such a curve is called a constant speed geodesics between $\rho_0$ and $\rho_1$. By [18, Lemma 3.30], any geodesic can be approximated by curves in $X_n$. If the pair $(\rho, \psi) \in E(\rho_0, \rho_1)$ attains the infimum in (2.5), then $\rho$ is a geodesic and satisfies the geodesic equations [10, Proposition 2.5]

\[
\begin{align*}
\partial_t \rho &= K(\rho)\psi, \\
\partial_t \psi &= -\frac{1}{2} \langle DK(\rho)[\cdot] \psi, \psi \rangle,
\end{align*}
\]

where the vector $b = \langle DK(\rho)[\cdot] \psi, \psi \rangle$ is defined by $\langle b, v \rangle = \langle DK(\rho)v \psi, \psi \rangle$ for $v \in \mathbb{R}^{n+1}$.

**Definition 1** (Displacement convexity) Let $\lambda \in \mathbb{R}$. We say that a functional $E : X_n \rightarrow \mathbb{R} \cup \{+\infty\}$ is displacement $\lambda$-convex on $X_n$ with respect to the metric $W$ if for any constant speed geodesic curve $\rho : [0,1] \rightarrow X_n$,

\[
E(\rho(t)) \leq (1-t)E(\rho(0)) + tE(\rho(1)) - \frac{\lambda}{2} t(1-t)W(\rho(0), \rho(1))^2, \quad t \in [0,1].
\]

If $\lambda = 0$, $E$ is simply called displacement convex. Moreover, if $t \mapsto E(\rho(t))$ is twice differentiable, $E$ is displacement $\lambda$-convex if and only if

\[
\frac{d^2}{dt^2} E(\rho(t)) \geq \lambda W(\rho(0), \rho(1))^2, \quad t \in [0,1].
\]

We show that displacement $\lambda$-convexity of $F$ is guaranteed if a certain matrix is positive semi-definite. This result is an analog of Proposition 2.1 in [21].

**Proposition 1** The entropy $F$, defined in (2.2), is displacement $\lambda$-convex for some $\lambda \in \mathbb{R}$ if and only if, for any $\rho \in X_n$,

\[
M(\rho) \geq \lambda K(\rho),
\]

i.e. $M(\rho) - \lambda K(\rho)$ is positive semi-definite, where

\[
M(\rho) = \frac{1}{2}(DK(\rho)[Q\phi(\rho)] - Q\Phi'(\rho)K(\rho) - K(\rho)\Phi'(\rho)Q^\top)
\]

and $\Phi'(\rho) = \text{diag}(\phi'(\rho_1), \ldots, \phi'(\rho_n))$.

**Proof** Let $\rho_0, \rho_1 \in X_n$ and let $\rho : [0,1] \rightarrow X_n$ be a geodesic curve with $(\rho, \psi) \in E(\rho_0, \rho_1)$. Then, $(\rho, \psi)$ satisfies the geodesic equations (2.6), implying that

\[
\frac{d}{dt} F(\rho) = \langle DF(\rho), \partial_t \rho \rangle = \langle DF(\rho), K(\rho)\psi \rangle.
\]

Differentiating a second time and using the symmetry of $K(\rho)$ and $DK(\rho)[\partial_t \rho]$, we find...
The no-flux boundary conditions are realized by setting
\[ \langle Q \rangle = 0 \]
with the discrete gradient
\[ \langle 3.1 \rangle \]
and
\[ \langle 3.2 \rangle \]
only if
\[ h \in D_{K} \rightarrow \langle Q \rangle = 0 \]
Displacement convexity

Inserting the geodesic equation (2.6) yields
\[
\frac{d^2}{dt^2} F(\rho) = \langle K(\rho)D^2 F(\rho)K(\rho) \rangle + DK(\rho)[\cdot]D F(\rho) = -Q(\rho)K(\rho). \tag{2.9}
\]
We differentiate $K(\rho)D F(\rho) = -Q(\rho)$ with respect to $\rho$:
\[
K(\rho)D^2 F(\rho) + DK(\rho)[\cdot]D F(\rho) = -Q(\rho). \tag{2.10}
\]
Thus, we can replace the first bracket on the right-hand side of (2.9) by $-Q(\rho)K(\rho)$:
\[
\frac{d^2}{dt^2} F(\rho) = \langle -Q(\rho)K(\rho), \psi \rangle + \frac{1}{2} \langle DK(\rho)[Q(\rho)], \psi \rangle \tag{2.10}
\]
We infer from (2.7) that
\[ \frac{d^2}{dt^2} F(\rho) \geq \lambda \langle K(\rho), \psi \rangle \]
for all geodesic curves $\rho$ and vector fields $\psi$ such that $(\rho, \psi) \in E(\rho_0, \rho_1)$. Consequently,
\[ \frac{d^2}{dt^2} F(\rho(t)) \geq \lambda \mathcal{W}(\rho_0, \rho_1)^2, \quad t \in [0, 1], \]
and by Definition 1, $F$ is displacement $\lambda$-convex.

For the only if part, given $\rho \in X_n$ and $\psi \in \mathbb{R}^n$, we construct a geodesic starting at $\rho$ with initial field $\psi$ and the result follows from (2.10).

3 Semi-discrete heat equation

As a warm-up, we consider the semi-discrete heat equation
\[ \partial_t \rho_i = h^{-2}(\rho_{i-1} - 2\rho_i + \rho_{i+1}), \quad i = 0, \ldots, n, \quad t > 0, \tag{3.1} \]
where $n \in \mathbb{N}$ and $h = 1/n > 0$. The no-flux boundary conditions are realized by setting $\rho_{-1} = \rho_0$ and $\rho_{n+1} = \rho_n$. We write $\rho = (\rho_0, \ldots, \rho_n)$. Equation (3.1) can be written as (2.1) by setting $\phi(s) = s$ and $Q = -G^T G$ with the discrete gradient $G \in \mathbb{R}^{n \times (n+1)}$, $G_{ij} = h^{-1}(\delta_{ij} - \delta_{i+1,j})$. By slightly abusing the notation, we set $w_i = 1$ for $i = 0, \ldots, n$ and note that for a function $f : [0, \infty) \rightarrow \mathbb{R}$, the corresponding entropy given in (2.2) reduces to
\[ F(\rho) = \sum_{i=0}^{n} f(\rho_i). \tag{3.2} \]
Then, for the respective Onsager operator given in (2.3) with the mean function $A^f$, we claim that the entropy $\mathcal{F}$ is displacement convex, under suitable conditions on $f$.

**Theorem 2** Let $f$ be such that $A^f$, defined in (1.1), is concave in both variables. Then the entropy (3.2) is displacement convex with respect to the metric (2.5) induced by $A^f$.

If $f(s) = s(\log s - 1)$ or $f(s) = s^\alpha$ for $1 < \alpha < 2$, $A$ is concave in both variables (see Lemma 9), thus fulfilling the assumption of the theorem.

**Proof** We formulate $Q\rho = -G^T \Gamma L(\rho)Gf' (\rho)$, where $L(\rho) = \text{diag}(A^f(\rho_i, \rho_{i+1}))_{i=0}^{n-1}$ and $f'(\rho) = (f' (\rho_i))_{i=0}^{n}$. Then, setting $K(\rho) = G^T L(\rho)G$, we can write (3.1) as the gradient system

$$
\partial_{\tau} \rho = Q\rho = -K(\rho)DF(\rho),
$$

where we identify $DF(\rho)$ with $f' (\rho)$. Thus, by Proposition 1, it is sufficient to show that the matrix $M(\rho)$, defined in (2.8), is positive semi-definite. In fact, because of the special structure of $K(\rho)$, we can simplify this condition. Let $\psi \in \mathbb{R}^{n+1}$. Then, using $DK(\rho)[\cdot] = G^T DL(\rho)[\cdot] G$ and $Q = -G^T G$,

$$
\langle M(\rho)\psi, \psi \rangle = \frac{1}{2} \left\langle (DK(\rho)[Q\rho] - QK(\rho) - K(\rho)Q^T)\psi, \psi \right\rangle = \frac{1}{2} \left\langle G^T (DL(\rho)[Q\rho]G + GG^T L(\rho)G + L(\rho)GG^T G)\psi, \psi \right\rangle = \frac{1}{2} \left\langle (DL(\rho)[Q\rho] + GG^T L(\rho) + L(\rho)GG^T G)G\psi, G\psi \right\rangle.
$$

Hence, it is sufficient to show that

$$
\tilde{M} := -DL(\rho)[G^T G\rho] + GG^T L(\rho) + L(\rho)GG^T
$$

is positive semi-definite.

We show this claim by verifying that $\tilde{M}$ is diagonally dominant. To this end, we observe that $\tilde{M}$ is a symmetric tridiagonal matrix with entries

$$
\tilde{M} = \frac{1}{h^2} \begin{pmatrix}
 a_0 & b_0 & 0 & \cdots & 0 \\
 b_0 & a_1 & b_1 & \ddots & \vdots \\
 0 & b_1 & \ddots & \ddots & 0 \\
 \vdots & \ddots & a_{n-2} & b_{n-2} \\
 0 & \cdots & 0 & b_{n-2} & a_{n-1}
\end{pmatrix},
$$

where the coefficients are given by

$$
a_i = 4A^f(\rho_i, \rho_{i+1}) - \partial_1 A^f(\rho_i, \rho_{i+1})(2\rho_i - \rho_{i-1} - \rho_{i+1}) - \partial_2 A^f(\rho_i, \rho_{i+1})(2\rho_{i+1} - \rho_{i-1} - \rho_{i+2}), \quad i = 0, \ldots, n - 1,
$$

$$
b_i = -(A^f(\rho_i, \rho_{i+1}) + A^f(\rho_{i+1}, \rho_{i+2})) \leq 0, \quad i = 0, \ldots, n - 2.
$$
We also set \( b_{-1} = -A^f(\rho_{-1}, \rho_0) - A^f(\rho_0, \rho_1) \leq 0 \) and \( b_{n-1} = -A^f(\rho_{n-1}, \rho_n) - A^f(\rho_n, \rho_{n+1}) \leq 0 \), where by the non-flux boundary conditions, we have \( \rho_{-1} = \rho_0 \) and \( \rho_{n+1} = \rho_n \).

The matrix \( M \) is diagonally dominant if

\[
\begin{align*}
    a_0 + b_0 & \geq 0, \quad a_{n-1} + b_{n-2} \geq 0, \\
    a_i + b_{i-1} + b_i & \geq 0 \quad \text{for } i = 1, \ldots, n - 2.
\end{align*}
\]

We will prove (3.4) for \( i = 0, \ldots, n - 1 \). The first two conditions (3.3) follow from (3.4) for \( i = -1 \) and \( i = n - 1 \), since \( a_0 + b_0 = (a_0 + b_{-1} + b_0) - b_{-1} \geq a_0 + b_{-1} + b_0 \geq 0 \) and \( a_{n-1} + b_{n-2} = (a_{n-1} + b_{n-2} + b_{n-1}) - b_{n-1} \geq a_{n-1} + b_{n-2} + b_{n-1} \geq 0 \). Thus, it remains to prove (3.4). We compute

\[
\begin{align*}
    a_i + b_{i-1} + b_i &= 2A^f(\rho_i, \rho_{i+1}) - A^f(\rho_{i+1}, \rho_{i+2}) - A^f(\rho_{i-1}, \rho_i) \\
    &- \partial_1 A^f(\rho_i, \rho_{i+1})(2\rho_i - \rho_{i-1} - \rho_{i+1}) - \partial_2 A^f(\rho_i, \rho_{i+1})(2\rho_{i+1} - \rho_i - \rho_{i+2}).
\end{align*}
\]

Since \( A^f \) is assumed to be concave, we may apply Lemma 8, which shows that this expression is non-negative, and hence, \( M \) is positive semi-definite.

For non-linear functions \( \phi \) and non-constant steady states \( (w_i) \), the proof of non-negativity of \( a_i + b_{i-1} + b_i \) is, unfortunately, not as simple as above, and we need more properties of the mean function. It turns out that the logarithmic mean satisfies these properties. Such a situation is considered in the next section.

## 4 Semi-discrete non-linear Fokker–Planck equations

We discretise the non-linear Fokker–Planck equation

\[
\partial_t \rho = \partial_x (\partial_x \phi(\rho) + \phi(\rho) \partial_x V) = \partial_x \left( \phi(\rho) \partial_x \log \frac{\phi(\rho)}{w} \right),
\]

where \( w(x) = e^{-V(x)} \) for \( V(x) = \gamma |x|^2 / 2 \) with \( \gamma \geq 0 \). Let \( n \in \mathbb{N}, h = 1/n > 0 \), and \( x_i = ih \). Approximating \( \rho(x_i, t) \) by \( \rho_i(t) \), \( w(x_i) \) by \( w_i \) and setting \( u_i = \phi(\rho_i)/w_i \), the numerical scheme reads as

\[
\partial_t \rho_i = h^{-2} \kappa_i (u_{i+1} - u_i) - h^{-2} \kappa_i (u_i - u_{i-1}),
\]

where \( \kappa_i = \sqrt{w_i w_{i+1}} \) approximates \( w(x_{i+1/2}) \). The no-flux boundary conditions are realized by \( u_{-1} = u_0 \) and \( u_{n+1} = u_n \). Setting \( Q = -G^\top \text{diag}(\kappa_i) G \text{diag}(w_i^{-1}) \) and, slightly abusing the notation, \( \rho = (\rho_0, \ldots, \rho_n) \), we see that the scheme can be formulated as \( \partial_t \rho = Q \phi(\rho) \), and thus, the framework of Section 2 applies. Hence, (4.1) can be written as the gradient system

\[
\partial_t \rho = -K(\rho) \log u, \quad K(\rho) = G^\top L(\rho) G,
\]

where \( \log u = (\log u_i)_{i=0}^n \),

\[
L(\rho) = \text{diag} (\kappa_i A(u_i, u_{i+1}))_{i=0}^{n-1}, \quad u_i = \frac{\phi(\rho_i)}{w_i},
\]

https://doi.org/10.1017/S0956792517000389 Published online by Cambridge University Press
and $A$ is the logarithmic mean. The above system can be written as in (2.4) by choosing $f(s) = s(\log s - 1)$, and therefore, by (2.2), the entropy reads as

$$F(\rho) = \sum_{i=0}^{n} \left( f(\rho_i) + \frac{1}{2} x_i^2 \rho_i \right),$$

since

$$f'(s) = f' \left( \frac{\phi(s)}{w_i} \right) = \log \phi(s) - \log w_i = f'(s) + \frac{1}{2} x_i^2, \quad i = 0, \ldots, n.$$ 

Thus, $D_F(\rho) = \log u$. By Proposition 1, we know that the convexity of $F$ is related to the matrix $M(\rho)$ defined in (2.8). Then, if $W$ is the non-local transportation distance defined in (2.5), we have the following results.

**Theorem 3** Let $\phi$ be invertible, $\phi' \circ \phi^{-1}$ be non-increasing, and $\gamma \geq 0$.

1. If $\gamma = 0$ then $M(\rho) \geq 0$, for all $\rho \in X_n$;
2. If $\gamma > 0$ then for each $\rho \in X_n$, there exist $\lambda_h(\rho) \in \mathbb{R}$ such that

$$M(\rho) \geq \lambda_h(\rho)K(\rho),$$

where

$$\lambda_h(\rho) = \gamma \left( \frac{2}{\gamma h^2}(1 - e^{-h^2/2}) \min_{i=0, \ldots, n} \phi'(\rho_i) - 2\cosh(\gamma h) \max_{i=0, \ldots, n} |\nabla_h \phi'(\rho_i)| \right) \in \mathbb{R}.$$

For every $(\rho, \psi) \in E(\rho_0, \rho_1)$, the entropy $F$ satisfies

$$\frac{d^2}{dt^2} F(\rho(t)) \geq \lambda_h(\rho(t)) \nu(\rho_0, \rho_1)^2, \quad t \in [0, 1].$$

If $\phi(s) = s$, we have $\lambda_h = (2/h^2)(1 - e^{-h^2/2}) \to \gamma$ as $h \to 0$.

The function $\phi(s) = s^\alpha$ satisfies the assumptions of the theorem if $0 < \alpha \leq 1$. In the linear case $\phi(s) = s$, we recover the result of [21]. Increasing non-linearities behaving like a power law $\phi(s) = s^\alpha$, $0 < \alpha \leq 1$, near zero and being linear at infinity also satisfy the assumptions of our theorem.

**Proof** First, note that for any $\gamma \geq 0$, we can calculate the derivative of $K(\rho)$ and obtain $DK(\rho)[\cdot] = G^T DL(\rho)[\cdot] G$, where

$$(DL(\rho)[\zeta])_i = \kappa_i \partial_1 A(u_i, u_{i+1}) \frac{\phi'(\rho_i)}{w_i} \xi_i + \kappa_i \partial_2 A(u_i, u_{i+1}) \frac{\phi'(\rho_{i+1})}{w_{i+1}} \xi_{i+1}$$

for $i = 0, \ldots, n - 1$ and $\zeta \in \mathbb{R}^{n+1}$. Therefore, for $\psi \in \mathbb{R}^{n+1}$,

$$\langle M(\rho) \psi, \psi \rangle = \frac{1}{2} \langle \{ G^T DL(\rho)[Q(\phi(\rho))] G + Q \Phi'(\rho) G^T L(\rho) G + G^T L(\rho) G \Phi'(\rho) Q^T \} \psi, \psi \rangle$$

$$= \frac{1}{2} \langle MG \psi, G \psi \rangle,$$
where
\[
\begin{aligned}
\tilde{M} &= DL(\rho)[Q\phi(\rho)] + \text{diag}(\kappa_i)G\text{diag}(w_i^{-1})\Phi'(\rho)G^\top L(\rho) \\
&\quad + L(\rho)G\Phi'(\rho)\text{diag}(w_i^{-1})G^\top \text{diag}(\kappa_i).
\end{aligned}
\]

This matrix is symmetric and tridiagonal with entries
\[
\tilde{M} = \frac{1}{h^2} \begin{pmatrix}
a_0 & b_0 & 0 & \cdots & 0 \\
b_0 & a_1 & b_1 & \ddots & \vdots \\
0 & b_1 & \ddots & 0 & 0 \\
\vdots & \ddots & \ddots & \ddots & \ddots \\
0 & \cdots & 0 & b_{n-2} & b_{n-2}
\end{pmatrix},
\]
where the coefficients are given by
\[
a_i = 2\kappa_i^2 A_i \left( \frac{\phi'(\rho_i)}{w_i} + \frac{\phi'(\rho_{i+1})}{w_{i+1}} \right) - \kappa_i \frac{\phi'(\rho_i)}{w_i} \partial_1 A_i (\kappa_{i-1}(u_i - u_{i-1}) + \kappa_i(u_i - u_{i+1})) \\
- \kappa_i \frac{\phi'(\rho_{i+1})}{w_{i+1}} \partial_2 A_i (\kappa_i(u_{i+1} - u_i) + \kappa_{i+1}(u_{i+1} - u_{i+2})), \quad i = 0, \ldots, n - 1
\]
\[
b_i = -\kappa_i \kappa_{i+1} \frac{\phi'(\rho_{i+1})}{w_{i+1}} (A_i + A_{i+1}) \leq 0, \quad i = 0, \ldots, n - 2
\]
and we abbreviated
\[
A_i := A(u_i, u_{i+1}), \quad \partial_j A_i := \partial_j A(u_i, u_{i+1}), \quad j = 1, 2.
\]

Using the non-flux boundary conditions, we can also define $b_{-1}$ and $b_{n-1}$ by the same expression as above. We show now that $\tilde{M} - \lambda hL(\rho)$ is diagonally dominant for some $\lambda \in \mathbb{R}$. For this, we introduce further abbreviations:
\[
\begin{aligned}
\alpha_i &= \kappa_i \frac{\phi'(\rho_i)}{w_i}, \quad \beta_i = \kappa_i \frac{\phi'(\rho_{i+1})}{w_{i+1}}.
\end{aligned}
\]

Since $\kappa_i \alpha_{i+1} = \kappa_{i+1} \beta_i$, we compute
\[
\begin{aligned}
a_i + b_{i-1} + b_i &= 2\kappa_i A_i (\alpha_i + \beta_i) - \kappa_i \beta_{i-1} (A_{i-1} + A_i) - \kappa_i \alpha_{i+1} (A_i + A_{i+1}) \\
- \kappa_i \alpha_i \partial_1 A_i (u_i - u_{i+1}) - \kappa_i \beta_i \partial_2 A_i (u_{i+1} - u_i) \\
- \kappa_i \alpha_{i-1} \partial_1 A_i (u_i - u_{i-1}) - \kappa_{i+1} \beta_i \partial_2 A_i (u_{i+1} - u_{i+2}) \\
= \kappa_i A_i (2\alpha_i + 2\beta_i - \beta_{i-1} - \alpha_{i+1}) \\
- \kappa_i \alpha_i \partial_1 A_i (u_i - u_{i+1}) - \kappa_i \beta_i \partial_2 A_i (u_{i+1} - u_i) \\
- \kappa_{i+1} (A_{i-1} - \partial_1 A_i u_{i-1}) - \kappa_{i+1} (A_{i+1} - \partial_2 A_i u_{i+2}) \\
- \kappa_{i-1} \alpha_i \partial_1 A_i u_i - \kappa_{i+1} \beta_i \partial_2 A_i u_{i+1} \\
= I_1 + \cdots + I_7.
\end{aligned}
\]

\[1113\]

Displacement convexity

Published online by Cambridge University Press

https://doi.org/10.1017/50956792517000389
We estimate these expressions term by term. Using property (ii) of Lemma 7, we find that

\[ I_2 = -\kappa_i x_i A_i + \kappa_i x_i \frac{A_i^2}{u_i}, \quad I_3 = -\kappa_i \beta_i A_i + \kappa_i \beta_i \frac{A_i^2}{u_{i+1}}. \]

The first terms on the right-hand sides cancel with some terms in \( I_1 \). By property (iv) of Lemma 7, it follows that

\[ I_4 \geq -\kappa_i \beta_{i-1} \max_{r \geq 0} \left( A(r, u_i) - \partial_1 A(u_i, u_{i+1}) r \right) = -\kappa_i \beta_{i-1} u_i \partial_2 A(u_i, u_{i+1}) \]

\[ I_5 \geq -\kappa_i x_{i+1} \max_{r \geq 0} \left( A(u_{i+1}, r) - \partial_2 A(u_i, u_{i+1}) r \right) = -\kappa_i x_{i+1} u_{i+1} \partial_2 A(u_i, u_{i+1}, u_i) \]

Finally, because of \( \kappa_i x_i = \kappa_{i+1} \beta_i \),

\[ I_6 = -\kappa_i \beta_{i-1} \partial_1 A_i u_i, \quad I_7 = -\kappa_i x_{i+1} \partial_2 A_i u_{i+1}. \]

Inserting these computations into (4.2), we arrive at

\[ a_i + b_{i-1} + b_i \geq \kappa_i A_i (x_i + \beta_i - \beta_{i-1} - x_{i+1}) + \kappa_i A_i^2 \left( \frac{x_i}{u_i} + \frac{\beta_i}{u_{i+1}} \right) - \kappa_i (\beta_{i-1} u_i + x_{i+1} u_{i+1}) \partial_1 A_i + \partial_2 A_i. \]

Employing property (iii) of Lemma 7 in the last term, we obtain

\[ a_i + b_{i-1} + b_i \geq \kappa_i A_i (x_i + \beta_i - \beta_{i-1} - x_{i+1}) + \kappa_i A_i^2 \left( \frac{x_i - x_{i+1}}{u_i} + \frac{\beta_i - \beta_{i-1}}{u_{i+1}} \right) \]

\[ = J_1 + J_2. \quad (4.3) \]

The idea is to replace \( \kappa_{i+1} \) in \( \beta_{i-1} \) and \( x_{i+1} \) by an expression involving only \( \kappa_i \). By definition of \( x_i \) and \( \beta_i \), and since

\[
\begin{align*}
\frac{K_{i+1}}{w_{i+1}} & = \frac{K_i}{w_i} \frac{K_{i+1}}{w_{i+1}} = \frac{K_i \sqrt{w_i w_{i+2}}}{w_{i+1}} = \frac{K_i}{w_i} e^{-\gamma h_i^2/2}, \\
\frac{K_{i-1}}{w_i} & = \frac{K_i}{w_{i+1}} \frac{K_{i-1}}{w_i} = \frac{K_i \sqrt{w_{i-1} w_{i+1}}}{w_i} = \frac{K_i}{w_{i+1}} e^{-\gamma h_i^2/2},
\end{align*}
\]

we find that

\[
J_1 = \kappa_i A_i \left( \frac{K_i}{w_i} \phi'(\rho_i) - \frac{K_{i+1}}{w_{i+1}} \phi'(\rho_{i+1}) + \frac{K_{i-1}}{w_{i+1}} \phi'(\rho_{i-1}) - \frac{K_i}{w_i} \phi'(\rho_i) \right) = \kappa_i^2 \frac{A_i}{w_{i+1}} \left( \phi'(\rho_i) - e^{-\gamma h_i^2/2} \phi'(\rho_{i+1}) \right) + \kappa_i^2 A_i \left( \phi'(\rho_{i+1}) - e^{-\gamma h_i^2/2} \phi'(\rho_i) \right).
\]
In the same way, since

\[ \kappa_{i+1} \frac{W_i}{W_{i+1}} = K_i \frac{\sqrt{W_i W_{i+2}}}{W_{i+1}} = K_i e^{-\gamma h^2/2}, \quad \kappa_{i-1} \frac{W_{i+1}}{W_i} = K_i \frac{\sqrt{W_{i-1} W_{i+1}}}{W_i} = K_i e^{-\gamma h^2/2}, \]

we infer that

\[ J_2 = \kappa_i A_i \left( \frac{\phi'(\rho_i)}{\phi(\rho_i)} - \kappa_{i+1} \frac{w_i}{w_{i+1}} \frac{\phi'(\rho_{i+1})}{\phi(\rho_i)} + \kappa_i \frac{\phi'(\rho_{i+1})}{\phi(\rho_{i+1})} - \kappa_{i-1} \frac{w_{i+1}}{w_i} \frac{\phi'(\rho_i)}{\phi(\rho_{i+1})} \right) \]

\[ = \kappa_i A_i \left( \frac{\phi'(\rho_i)}{\phi(\rho_i)} - e^{-\gamma h^2/2} \frac{\phi'(\rho_{i+1})}{\phi(\rho_{i+1})} + \frac{\phi'(\rho_{i+1})}{\phi(\rho_{i+1})} - e^{-\gamma h^2/2} \frac{\phi'(\rho_i)}{\phi(\rho_i)} \right). \]

Thus, (4.3) becomes

\[ a_i + b_{i-1} + b_i \geq \kappa_i A_i \left( \frac{\phi'(\rho_i)}{w_i} - e^{-\gamma h^2/2} \frac{\phi'(\rho_{i+1})}{w_{i+1}} + \frac{\phi'(\rho_{i+1})}{w_{i+1}} - e^{-\gamma h^2/2} \frac{\phi'(\rho_i)}{w_i} \right) \]

\[ + \kappa_i A_i \left( \frac{\phi'(\rho_i)}{\phi(\rho_i)} - e^{-\gamma h^2/2} \frac{\phi'(\rho_{i+1})}{\phi(\rho_{i+1})} + \frac{\phi'(\rho_{i+1})}{\phi(\rho_{i+1})} - e^{-\gamma h^2/2} \frac{\phi'(\rho_i)}{\phi(\rho_i)} \right) \]

\[ = \kappa_i A_i \frac{\phi'(\rho_i)}{\phi(\rho_i)} - \phi'(\rho_{i+1}) \left( A(u_i, u_{i+1}) \left( \frac{1}{\phi(\rho_i)} - \frac{1}{\phi(\rho_{i+1})} \right) + \frac{1}{w_i} - \frac{1}{w_{i+1}} \right) \]

\[ + \kappa_i A_i \left( 1 - e^{-\gamma h^2/2} \right) \left[ \frac{\phi'(\rho_i)}{w_{i+1}} + \frac{\phi'(\rho_{i+1})}{w_i} \right] + A(u_i, u_{i+1}) \left( \frac{\phi'(\rho_i) w_{i+1}}{u_{i+1}} + \frac{\phi'(\rho_{i+1}) w_i}{u_i} \right) \]

\[ = K_1 + K_2. \quad (4.4) \]

At this point, let us assume that \( \gamma = 0 \). Then, \( K_2 = 0 \). For \( K_1 \), note that in this case \( w_i = 1 \) for all \( i = 0, \ldots, n \) and

\[ (\phi'(\rho_i) - \phi'(\rho_{i+1})) \left( \frac{1}{\phi(\rho_i)} - \frac{1}{\phi(\rho_{i+1})} \right) \geq 0. \quad (4.6) \]

since \( \phi' \circ \phi^{-1} \) is non-increasing. This implies \( K_1 \geq 0 \) and therefore, \( M(\rho) \) is diagonally dominant.

Now, let us assume that \( \gamma > 0 \). We estimate \( K_2 \) using property (v) of Lemma 7:

\[ K_2 \geq 2 \kappa_i A_i \left( 1 - e^{-\gamma h^2/2} \right) \left( \frac{\phi'(\rho_i)}{w_{i+1}} + \frac{\phi'(\rho_{i+1})}{w_i} + 2 \sqrt{\frac{\phi'(\rho_i) \phi'(\rho_{i+1})}{w_i w_{i+1}}} \right) \]

\[ \geq 2 \kappa_i A_i \left( 1 - e^{-\gamma h^2/2} \right) \sqrt{\phi'(\rho_i) \phi'(\rho_{i+1})} \geq 2 \kappa_i A_i \left( 1 - e^{-\gamma h^2/2} \right) \min_{j=0, \ldots, n} \phi'(\rho_j). \]
By (4.6), since $A(u_i, u_{i+1}) \geq 0$ and $\sinh(s) \leq s \cosh(s)$ for $s \geq 0$,

$$K_1 \geq \kappa_i^2 A_i \left( \phi'(\rho_i) - \phi'(\rho_{i+1}) \right) \left( \frac{1}{w_i} - \frac{1}{w_{i+1}} \right)$$

$$= \kappa_i A_i \left( \phi'(\rho_i) - \phi'(\rho_{i+1}) \right) \left( \frac{w_{i+1}}{w_i} - \frac{w_i}{w_{i+1}} \right)$$

$$= -\kappa_i A_i \left( \phi'(\rho_i) - \phi'(\rho_{i+1}) \right) \left( e^{(x_{i+1}^2 - x_i^2)/4} - e^{-(x_{i+1}^2 - x_i^2)/4} \right)$$

$$\geq -2\kappa_i A_i h \max_{j=0,...,n} |\nabla_h \phi' (\rho_j) \sinh \left( \frac{\gamma}{4} (2i + 1) h^2 \right)$$

$$\geq -2\kappa_i A_i h \max_{j=0,...,n} |\nabla_h \phi' (\rho_j) \left( \frac{\gamma}{4} (2i + 1) h^2 \right) \cosh \left( \frac{\gamma}{4} (2i + 1) h^2 \right)$$

$$\geq -2\kappa_i A_i h^2 \max_{j=0,...,n} |\nabla_h \phi' (\rho_j) | \gamma \cosh(\gamma h),$$

where we recall that $|\nabla_h \phi' (\rho_j)| := h^{-1} |\phi'(\rho_i) - \phi'(\rho_{i+1})|$ and we used $ih \leq 1$. Then, (4.5) yields

$$h^{-2} \left( a_i + b_{i-1} + b_i \right) \geq \gamma \kappa_i A_i \left( \frac{2}{\gamma h^2} (1 - e^{-\gamma h^2/2}) \min_{j=0,...,n} \phi'(\rho_j) \right.$$

$$- 2 \cosh(\gamma h) \max_{j=0,...,n} |\nabla_h \phi' (\rho_j) | \left) \right)$$

$$= \lambda_h \kappa_i A_i.$$  

This proves that $\tilde{M} - \lambda_h L(\rho)$ is positive semi-definite, finishing the proof. \hfill \Box

From numerical analysis and the expected large-time asymptotics of the equations involved, we expect that $\min_{i=0,...,n} \phi'(\rho_i)$ and $\max_{i=0,...,n} |\nabla_h \phi' (\rho_i)|$ are independent of $h$ and bounded only by discrete norms of $\rho(0)$ under suitable assumptions on $\phi$. In Appendix B, we provide these a priori estimates for the case $\gamma = 0$ and very small initial data, as an indication that they might hold true for the case $\gamma > 0$.

In the case $\gamma > 0$, since $\lambda_h (\rho)$ depends on $\rho$, we need to be careful with the definition of displacement convexity. As explained in the previous paragraph, it is expected that $\lambda_h (\rho)$ can be bounded in terms of $\rho(0) = \rho_0$. Thus, if $|\rho_0| \leq C$ for some constant $C > 0$, $\lambda_h (\rho)$ does not depend on $\rho$ and the standard notion of displacement convexity makes sense. Another issue arises since the space $X_n$ is not complete. However, it is shown in [8] that a geodesically $\lambda$-convex gradient system on $X_n$ can be extended to the completion $\overline{X}_n$, which is again a geodesically $\lambda$-convex gradient system. We refer to [21, Section 3.3] for a detailed discussion on this issue.

**Remark 4** In the case $\gamma = 0$, the previous result implies that the entropy

$$\mathcal{F}(\rho) = \sum_{i=0}^n f(\rho_i) \text{ with } f'(s) = \log(\phi(s))$$
Displacement convexity is convex along solutions of the semi-discrete diffusion equation

$$\partial_t \rho_i = \frac{\phi(\rho_{i-1}) - 2\phi(\rho_i) + \phi(\rho_{i+1})}{h^2}, \quad i = 0, \ldots, n,$$

where $\rho_{-1} = \rho_0$ and $\rho_{n+1} = \rho_n$ and $\phi(s) = s^2$ for $0 < \alpha \leq 1$.

The following remark, based on an idea of [10], shows that the standard entropy for the diffusion equation is not displacement convex along the solutions.

**Remark 5** Erbar and Maas [10] considered the diffusion equation in the form

$$\partial_t \rho = \Delta \phi(\rho) = \text{div}(\rho \nabla U'(\rho)),$$

where $U$ satisfies $sU''(s) = \phi'(s)$. The corresponding numerical scheme becomes

$$\partial_t \rho = -K(\rho)U'(\rho), \quad K(\rho) = G^\top L(\rho)G,$$

where $U'(\rho) = (U'(\rho_0), \ldots, U'(\rho_n))$ and the operator $L(\rho)$ is again defined by $L(\rho) = \text{diag}(A(\rho_i, \rho_{i+1}))$, but with the mean function

$$A(\rho_i, \rho_{i+1}) = \frac{\phi(\rho_i) - \phi(\rho_{i+1})}{U'(\rho_i) - U'(\rho_{i+1})}. \quad (4.7)$$

The associated entropy is $F(\rho) = \sum_{i=0}^n U(\rho_i)$. We show next that $F(\rho)$ is not displacement convex in general. Indeed, if $\rho$ is a geodesic curve on $X_n$ with respect to the non-linear transportation metric $W$ induced by (4.7), then,

$$\frac{d^2}{dt^2}F(\rho) = \frac{1}{2} \langle \tilde{M}(\rho)G\psi, G\psi \rangle, \quad (4.8)$$

where $\tilde{M} = DL(\rho)[Q\phi(\rho)] + G\Phi'(\rho)G^\top L(\rho) + L(\rho)G\Phi'(\rho)G^\top$. In fact, $\tilde{M}$ is the tridiagonal matrix

$$\tilde{M} = \frac{1}{h^2} \begin{pmatrix} d_0 & c_0 & 0 & \cdots & 0 \\ c_0 & d_1 & c_1 & \ddots & \vdots \\ 0 & c_1 & \ddots & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & c_{n-2} \\ 0 & \cdots & 0 & c_{n-2} & d_{n-1} \end{pmatrix},$$

with the matrix coefficients

$$d_i = 2A(\rho_i, \rho_{i+1})(\phi'(\rho_i) + \phi'(\rho_{i+1})) + \partial_1 A(\rho_i, \rho_{i+1})(\phi(\rho_{i-1}) - 2\phi(\rho_i) + \phi(\rho_{i+1}))$$

$$+ \partial_2 A(\rho_i, \rho_{i+1})(\phi(\rho_i) - 2\phi(\rho_{i+1}) + \phi(\rho_{i+2})), \quad i = 1, \ldots, n - 1,$$

$$c_i = -\phi'(\rho_{i+1})(A(\rho_i, \rho_{i+1}) + A(\rho_{i+1}, \rho_{i+2})), \quad i = 1, \ldots, n - 2.$$
If \( \phi(s) = s^2 \), we have \( A(s, t) = (s + t)/2 \) and the second principal minor equals

\[
d_0d_1 - c_0^2 = \frac{1}{2} \rho_0^2 \rho_1^2 + \frac{3}{2} \rho_0^2 \rho_2^2 + 4 \rho_0 \rho_1 \rho_2 \rho_3 + \frac{3}{2} \rho_0^2 \rho_3^2 + \frac{1}{2} \rho_0^2 \rho_4^2 + \rho_0 \rho_1^2 + 3 \rho_0 \rho_1 \rho_2^2 + 8 \rho_0 \rho_1 \rho_2 \rho_3 + 3 \rho_0 \rho_1 \rho_3^2 + \rho_0 \rho_1 \rho_4^2 + \frac{1}{4} \rho_1^4 + 2 \rho_1^2 \rho_2 \rho_3 + \frac{3}{4} \rho_1^2 \rho_3^2 + \frac{1}{4} \rho_1^2 \rho_4^2 + \frac{13}{4} \rho_2^4 - 2 \rho_2 \rho_3 - \frac{1}{4} \rho_2^2 \rho_3^2 + \frac{1}{4} \rho_2^2 \rho_4^2.
\]

The coefficient \(-13/4\) of the highest power in \( \rho_2 \) is negative and therefore, the second principal minor may be negative. According to Sylvester’s criterion, \( \tilde{M} \) is not positive semi-definite. By choosing as initial data a vector of positive densities and the direction \( \psi \) such that the right-hand side of (4.8) is negative at \( t = 0 \), we achieve that \( \frac{d}{dt} \mathcal{F}(\rho) < 0 \) for a small time interval. Therefore, the entropy fails to be convex at time \( t = 0 \).

**Remark 6** We point out that showing the convergence of the numerical scheme could be done by looking at the convergence of the metric structures from the discrete to the continuum setting. A result in this direction was obtained in [10, Theorem 5.1] using Gromov–Hausdorff convergence arguments. It is an open problem to generalise it to the present setting.

**Acknowledgement**

The authors warmly thank the Mittag-Leffler Institute for providing a marvellous atmosphere for research while this paper was being finalised.

**References**

[1] Ambrosio, L., Gigli, N. & Savaré, G. (2005) Gradient Flows in Metric Spaces and in the Space of Probability Measures. Lectures in Mathematics, Birkhäuser, Basel.

[2] Bessemsomun-Chatard M. (2012) A finite volume scheme for convection-diffusion equations with nonlinear diffusion derived from the Scharfetter-Gummel scheme. *Numer. Math.* 121, 637–670.

[3] Bonciocat, A.-I. & Sturm, K.-T. (2009) Mass transportation and rough curvature bounds for discrete spaces. *J. Funct. Anal.* 256, 2944–2966.

[4] Caputo, P., Dai Pra, P. & Posta, G. (2009) Convex entropy decay via the Bochner–Bakry–Emery approach. *Ann. Inst. H. Poincaré Prob. Stat.* 45, 734–753.

[5] Carrillo, J. A., McCann, R. & Villani, C. (2006) Contractions in the 2-Wasserstein length space and thermalization of granular media. *Arch. Ration. Mech. Anal.* 179, 217–263.

[6] Carrillo, J. A., Lisini, S., Savaré, G. & Slepčev, D. (2010) Nonlinear mobility continuity equations and generalized displacement convexity. *J. Funct. Anal.* 258, 1273–1309.

[7] Chow, S., Huang, W., Li, Y. & Zhou, H. (2012) Fokker–Planck equations for a free energy functional or Markov process on a graph. *Arch. Ration. Mech. Anal.* 203, 969–1008.

[8] Daneri, S. & Savaré, G. (2008) Eulerian calculus for the displacement convexity in the Wasserstein distance. *SIAM J. Math. Anal.* 40, 1104–1122.

[9] Erbar, M. & Maas, J. (2012) Ricci curvature bounds for finite Markov chains via convexity of the entropy. *Arch. Ration. Mech. Anal.* 206, 997–1038.

[10] Erbar, M. & Maas, J. (2014) Gradient flow structures for discrete porous medium equations. *Discrete Contin. Dyn. Sys.* 34, 1355–1374.
Appendix A Properties of mean functions

We need some properties of the mean function

$$A^I(s, t) = \frac{s - t}{f'(s) - f'(t)} \quad \text{for } s \neq t, \quad A^I(s, s) = \frac{1}{f''(s)}, \quad (A.1)$$

which we recall here. First, we are concerned with the logarithmic mean, i.e., $f'(s) = \log s$, for which we write simply $A$.

Lemma 7 (Properties of the logarithmic mean) For all $s, t > 0$, we have

(i) \quad $A(s, t) = A(t, s), \quad \partial_1 A(s, t) = \partial_2 A(t, s),$

(ii) \quad $\partial_1 A(s, t) = \frac{A(s, t)(s - A(s, t))}{s(s - t)}, \quad s \neq t,$

(iii) \quad $\partial_1 A(s, t) + \partial_2 A(s, t) = \frac{A(s, t)^2}{st},$

(iv) \quad $\max_{r \geq 0} \left( A(r, t) - \partial_1 A(t, s)r \right) = t\partial_1 A(s, t),$

(v) \quad $A(s, t) \left( \frac{a}{s} + \frac{b}{t} \right) \geq 2\sqrt{ab} \quad \text{for } a, b > 0.$
Properties (i)–(iii) can be easily verified by a calculation. Properties (iv)–(v) are shown in [21, Appendix A].

**Lemma 8** Let \( \Lambda \in C^1([0, \infty)^2) \) be any function being concave in both variables, and let \( u_0, u_1, u_2, u_3 \geq 0 \). Then,

\[
-\Lambda(u_0, u_1) + 2\Lambda(u_1, u_2) - \Lambda(u_2, u_3) \\
\geq \partial_1\Lambda(u_1, u_2)(-u_0 + 2u_1 - u_2) + \partial_2\Lambda(u_1, u_2)(-u_1 + 2u_2 - u_3). 
\]

**(A 2)**

**Proof** Since \( \Lambda \) is concave in both variables, we have

\[
\Lambda(u_0, u_1) - \Lambda(u_1, u_2) \leq \partial_1\Lambda(u_1, u_2)(u_0 - u_1) + \partial_2\Lambda(u_1, u_2)(u_1 - u_2), \\
\Lambda(u_2, u_3) - \Lambda(u_1, u_2) \leq \partial_1\Lambda(u_1, u_2)(u_2 - u_1) + \partial_2\Lambda(u_1, u_2)(u_3 - u_2),
\]

and adding both inequalities gives the conclusion. \( \square \)

**Lemma 9** *(Concavity of mean functions)* Let \( \Lambda^{f} : [0, \infty)^2 \to \mathbb{R} \) be given by (A 1) and let either \( f(s) = s(\log s - 1) \) or \( f(s) = s^\alpha \), where \( 1 < \alpha \leq 2 \). Then \( \Lambda^{f} \) is concave in both variables.

**Proof** For \( f(s) = s(\log s - 1) \), we refer to [9, Section 2]. The statement for \( f(s) = s^\alpha \) is proved in [15, Appendix]. \( \square \)

**Appendix B a priori estimates**

**Lemma 10** *(a priori estimates)* Let \( \phi \) be non-decreasing, \( h > 0 \) and let \( \rho = (\rho_0, \ldots, \rho_n) \in C^1([0, T^*]; \mathbb{R}^{n+1}) \) for some \( T^* > 0 \) be the solution to

\[
h^2\partial_t \rho_i = \phi(\rho_{i-1}) - 2\phi(\rho_i) + \phi(\rho_{i+1}), \quad i = 0, \ldots, n, 
\]

\( (B 1) \)

where \( \rho_0 = \rho_{n+1} = \rho_n \). Then, for all \( i = 0, \ldots, n \) and \( t > 0 \),

\[
\min_{i=0,\ldots,n} \rho_i(0) \leq \rho_i(t) \leq \max_{i=0,\ldots,n} \rho_i(0), 
\]

\( (B 2) \)

\[
\max_{i=0,\ldots,n} |\nabla_h^i \phi(\rho_i(t))| \leq h^{-1/2} |\nabla_h \phi(\rho(0))|_2, 
\]

\( (B 3) \)

where \( \nabla_h \phi(\rho_i(t)) = h^{-1}(\phi(\rho_{i+1}(t)) - \phi(\rho_{i}(t))) \) and

\[
|\nabla_h \phi(\rho(0))|_2 := \left( \sum_{i=0}^{n} h|\nabla_h \phi(\rho_i(0))|^2 \right)^{1/2}. 
\]

\( (B 4) \)
Proof We multiply (B 1) by \((\rho_i - M)_+ = \max\{0, \rho_i - M\}\) and sum over \(i = 0, \ldots, n\):

\[
\frac{h^2}{2} \partial_t \sum_{i=0}^{n} (\rho_i - M)_+^2
= \sum_{i=0}^{n} (\phi(\rho_{i-1}) - \phi(\rho_i))(\rho_i - M)_+ - \sum_{i=0}^{n} (\phi(\rho_i) - \phi(\rho_{i+1}))(\rho_i - M)_+
= \sum_{j=0}^{n} (\phi(\rho_j) - \phi(\rho_{j+1}))(\rho_{j+1} - M)_+ - \sum_{i=0}^{n} (\phi(\rho_i) - \phi(\rho_{i+1}))(\rho_i - M)_+
= - \sum_{i=0}^{n} (\phi(\rho_i) - \phi(\rho_{i+1}))(\rho_i - M)_+ - (\rho_{i+1} - M)_+ \leq 0,
\]

since \(\phi\) is non-decreasing. This shows that

\[
\sum_{i=0}^{n} (\rho_i(t) - M)_+^2 \leq \sum_{i=0}^{n} (\rho_i(0) - M)_+^2.
\]

Thus, if \(M = \max_{i=0, \ldots, n} \rho_i(0)\), the upper bound in (B 2) follows. The lower bound is proved analogously.

For the proof of (B 3), we compute

\[
\frac{h^2}{2} \partial_t \sum_{i=0}^{n-1} (\phi(\rho_{i+1}) - \phi(\rho_i))^2 = h^2 \sum_{i=0}^{n-1} (\phi(\rho_{i+1}) - \phi(\rho_i))(\phi'(\rho_{i+1})\partial_t \rho_{i+1} - \phi'(\rho_i)\partial_t \rho_i)
= \sum_{i=0}^{n-1} (\phi(\rho_{i+1}) - \phi(\rho_i))\phi'(\rho_{i+1})(\phi(\rho_i) - 2\phi(\rho_{i+1}) + \phi(\rho_{i+2}))
- \sum_{i=0}^{n-1} (\phi(\rho_{i+1}) - \phi(\rho_i))\phi'(\rho_i)(\phi(\rho_{i-1}) - 2\phi(\rho_i) + \phi(\rho_{i+1})).
\]

Making the change of variables \(i \mapsto i - 1\) in the first sum and rearranging the terms, we find that

\[
\frac{h^2}{2} \partial_t \sum_{i=0}^{n-1} (\phi(\rho_{i+1}) - \phi(\rho_i))^2 = - \sum_{i=0}^{n} \phi'(\rho_i)(\phi(\rho_{i-1}) - 2\phi(\rho_i) + \phi(\rho_{i+1}))^2 \leq 0.
\]

Consequently, for any \(j = 0, \ldots, n - 1\) and \(t > 0\),

\[
(\phi(\rho_{j+1}(t)) - \phi(\rho_j(t)))^2 \leq \sum_{i=0}^{n-1} (\phi(\rho_{i+1}(t)) - \phi(\rho_i(t)))^2
\leq \sum_{i=0}^{n-1} (\phi(\rho_{i+1}(0)) - \phi(\rho_i(0)))^2 = h|\nabla_h \phi(\rho(0))|^2.
\]

Taking the maximum over \(j = 0, \ldots, n - 1\) shows (B 3).
Corollary 11 Let $\phi$ be non-decreasing and invertible, $h > 0$, and let $\rho = (\rho_0, \ldots, \rho_n)$ be the solution to (B 1). We assume that $m := \min_{i=0, \ldots, n} \rho_i(0) > 0$ and set $M := \max_{i=0, \ldots, n} \rho_i(0)$. Then,

$$\max_{i=0, \ldots, n} |\nabla_h \phi'(\rho_i)| \leq h^{-1/2} \max_{s \in [\phi^{-1}(m), \phi^{-1}(M)]} \frac{|\phi''(s)|}{\phi'(s)} |\nabla_h \phi(0)|_2, \quad (B 5)$$

where $|\nabla_h \phi(0)|_2$ is defined in (B 4).

Proof First, note that $m \leq \rho_i(t) \leq M$ for all $i = 0, \ldots, n$ and $t > 0$, by Lemma 10. Then the result follows from the mean value theorem. Indeed, we have for some $\xi$ between $\rho_{i+1}$ and $\rho_i$,

$$h^{-1} |\phi'(\rho_{i+1}) - \phi'(\rho_i)| = \frac{1}{h} |(\phi' \circ \phi^{-1})(\phi(\rho_{i+1})) - (\phi' \circ \phi^{-1})(\phi(\rho_i))|$$

$$= \frac{1}{h} \left| \frac{\phi''(\phi^{-1}(\xi))}{\phi'(\phi^{-1}(\xi))} \right| |\phi(\rho_{i+1}) - \phi(\rho_i)|$$

$$\leq \frac{1}{h} \max_{s \in [\phi^{-1}(m), \phi^{-1}(M)]} \frac{|\phi''(s)|}{\phi'(s)} \max_{j=0, \ldots, n} |\phi(\rho_{j+1}) - \phi(\rho_j)|,$$

and we conclude after applying (B 3).

Example 1 Let $\phi(s) = s^\alpha$ for $\alpha \in (0, 1)$, $h > 0$ and let $\rho = (\rho_0, \ldots, \rho_n)$ be the solution to (B 1) with $m := \min_{i=0, \ldots, n} \rho_i(0) > 0$ and $M := \max_{i=0, \ldots, n} \rho_i(0)$. We claim that

$$\min_{i=0, \ldots, n} \phi'(\rho_i) \leq \alpha M^{\alpha-1}, \quad \max_{i=0, \ldots, n} |\nabla_h \phi'(\rho_i)| \leq (1 - \alpha) m^{-1/2} h^{-1/2} |\nabla_h \phi(0)|_2,$$

where $|\nabla_h \phi(0)|_2$ is defined in (B 4). Indeed, the first statement follows from $\alpha < 1$ and (B 2):

$$\min_{i=0, \ldots, n} \phi'(\rho_i) = \alpha \left( \max_{i=0, \ldots, n} \rho_i \right)^{\alpha-1} \leq \alpha M^{\alpha-1},$$

and the second statement is a consequence of Corollary 11 evaluating the right-hand side of (B 5).