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On Gaussian Brunn-Minkowski inequalities

Franck Barthe and Nolwen Huet

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1 Introduction

In this paper, we are interested in Gaussian versions of the classical Brunn-Minkowski inequality on the Lebesgue measure of sum-sets (see e.g. [21, 22]). On \mathbb{R}^n with its canonical Euclidean structure $(\langle \cdot, \cdot \rangle, |\cdot|)$ we consider the standard Gaussian measure $\gamma_n(dx) = (2\pi)^{-n/2} \exp(-|x|^2/2) dx$, $x \in \mathbb{R}^n$. Given $\alpha, \beta \in \mathbb{R}$ and sets $A, B \subset \mathbb{R}^n$, we recall that their Minkowski combination is defined by

$$\alpha A + \beta B = \{\alpha a + \beta b; (a, b) \in A \times B\}.$$

Using symmetrization techniques, Ehrhard [17] proved a sharp lower bound on the Gaussian measure of a convex combination of convex sets. Namely: if $\alpha, \beta \geq 0$ satisfy $\alpha + \beta = 1$ and if $A, B \subset \mathbb{R}^n$ are convex, then

$$\Phi^{-1} \circ \gamma_n(\alpha A + \beta B) \geq \alpha \Phi^{-1} \circ \gamma_n(A) + \beta \Phi^{-1} \circ \gamma_n(B),$$

where Φ is the cumulative distribution function of γ_1 . This inequality becomes an equality when A and B are parallel half-spaces. Latała [19] showed that the inequality remains valid when A is convex and B is an arbitrary Borel set. In the remarkable paper [10], Borell was able to remove the remaining convexity assumption. He actually derived a functional version of the inequality (in the spirit of the Prékopa-Leindler inequality) by a wonderful interpolation technique based on the heat equation. In a series of papers, Borell extended the inequality to more general combinations:

Theorem (Borell [13]). *Let $\alpha_1, \dots, \alpha_m > 0$. The inequality*

$$\Phi^{-1} \circ \gamma_n\left(\sum \alpha_i A_i\right) \geq \sum \alpha_i \Phi^{-1} \circ \gamma_n(A_i) \tag{1}$$

holds for all Borel sets A_1, \dots, A_m in \mathbb{R}^n if and only if

$$\sum \alpha_i \geq 1 \quad \text{and} \quad \forall j, \alpha_j - \sum_{i \neq j} \alpha_i \leq 1.$$

Moreover, it holds for all convex sets A_1, \dots, A_m in \mathbb{R}^n if and only if $\sum \alpha_i \geq 1$.

He established the case $m = 2$ for Borel sets in [12] thanks to his semigroup argument. His proof in [13] of the general case relies on a tricky and somewhat complicated induction. Remark that a linear combination of Borel sets need not be a Borel set; however it is analytic or Suslin, hence universally measurable, see e.g. [18].

In this note we give a slight extension of the above statement. More importantly we propose a streamlined version of the semigroup argument for m functions directly, which allows to take advantage of convexity type assumptions. This better understanding of the semigroup technique also allows to study more general situations. The main result is stated next. It involves the heat semigroup, for which we recall the definition: given a Borel nonnegative function f on \mathbb{R}^n , its evolute at time $t \geq 0$ is the function $P_t f$ given by

$$P_t f(x) = \int f(x + \sqrt{t}y) \gamma_n(dy) = \mathbb{E}(f(x + B_t))$$

where B is an n -dimensional Brownian motion. By convention $\infty - \infty = -\infty$.

Theorem 1. Let $I_{conv} \subset \{1, \dots, m\}$, $\alpha_1, \dots, \alpha_m > 0$. The following assertions are equivalent:

1. The parameter α satisfies

$$\sum \alpha_i \geq 1 \quad \text{and} \quad \forall j \notin I_{conv}, \quad \alpha_j - \sum_{i \neq j} \alpha_i \leq 1. \quad (2)$$

2. For all Borel sets A_1, \dots, A_m in \mathbb{R}^n such that A_i is convex when $i \in I_{conv}$,

$$\Phi^{-1} \circ \gamma \left(\sum_i \alpha_i A_i \right) \geq \sum \alpha_i \Phi^{-1} \circ \gamma(A_i)$$

3. For all Borel functions f_0, f_1, \dots, f_m from \mathbb{R}^n to $[0, 1]$ such that $\Phi^{-1} \circ f_i$ is concave when $i \in I_{conv}$, if

$$\forall x_1, \dots, x_m \in \mathbb{R}^n, \quad \Phi^{-1} \circ f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ f_i(x_i),$$

then

$$\Phi^{-1} \left(\int f_0 d\gamma \right) \geq \sum \alpha_i \Phi^{-1} \left(\int f_i d\gamma \right).$$

4. For all Borel functions f_0, f_1, \dots, f_m from \mathbb{R}^n to $[0, 1]$ such that $\Phi^{-1} \circ f_i$ is concave when $i \in I_{conv}$, if

$$\forall x_1, \dots, x_m \in \mathbb{R}^n, \quad \Phi^{-1} \circ f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ f_i(x_i),$$

then for all $t \geq 0$

$$\forall x_1, \dots, x_m \in \mathbb{R}^n, \quad \Phi^{-1} \circ P_t f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ P_t f_i(x_i).$$

Remark. Condition (2) can be rephrased as $\sum \alpha_i \geq \max(1, \max\{2\alpha_j - 1; j \notin I_{conv}\})$. Actually the condition will come up in our argument in the following geometric form: there exist vectors $u_1, \dots, u_m \in \mathbb{R}^m$ such that for all $i \in I_{conv}$, $|u_i| \leq 1$, for all $i \notin I_{conv}$, $|u_i| = 1$ and $|\sum_i \alpha_i u_i| = 1$.

In the next section we show that the condition on α implies the fourth (and formally strongest) assumption in the latter theorem, when restricted to smooth enough functions. The third section completes the proof of the theorem. In the final section we discuss related problems.

Before going further, let us introduce some notation.

- We consider functions depending on a time variable t and a space variable x . The time derivative is denoted by ∂_t , while the gradient, Hessian and Laplacian in x are denoted by ∇_x , Hess_x and Δ_x , omitting the index x when there is no ambiguity.
- The unit Euclidean (closed) ball and sphere of \mathbb{R}^d are denoted respectively by \mathbb{B}^d and \mathbb{S}^{d-1} .
- For $A \subset \mathbb{R}^d$, we set $A^\varepsilon = A + \varepsilon \mathbb{B}^d$.

2 Functional and semigroup approach

As already mentioned we follow Borell's semigroup approach of the Gaussian Brunn-Minkowski inequalities (see [10] and [12]): for parameters α verifying (2), the plan is two show the functional version of the inequality (the third assertion of Theorem 1), by means of the heat semigroup. Note that the fourth assertion implies the third one when choosing $t = 1$, and $x_i = 0$. So our aim is to establish the fourth assumption. More precisely, given Borel functions f_0, f_1, \dots, f_m from \mathbb{R}^n taking to $(0, 1)$, we define C on $[0, T] \times (\mathbb{R}^n)^m$ by

$$C(t, x) = C(t, x_1, \dots, x_m) = \Phi^{-1} \circ P_t f_0(\sum \alpha_i x_i) - \sum \alpha_i \Phi^{-1} \circ P_t f_i(x_i),$$

Since $P_0 f = f$ the assumption

$$\forall x_i \in \mathbb{R}^n, \quad \Phi^{-1} \circ f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ f_i(x_i) \quad (3)$$

translates as $C(0, \cdot) \geq 0$. Our task is to prove

$$C(0, \cdot) \geq 0 \implies \forall t \geq 0, C(t, \cdot) \geq 0.$$

2.1 Preliminaries

When the functions f_i are smooth enough, the time evolution of $P_t f_i$ is described by the heat equation. This yields a differential equation satisfied by C . Our problem boils down to determine whether this evolution equation preserves nonnegative functions. This is clearly related to the maximum principle for parabolic equations (see e.g. [15]). We will use the following lemma:

Lemma 1. *Assume that C is twice differentiable. If*

$$\begin{cases} \text{Hess}(C) \geq 0 \\ \nabla C = 0 \\ C \leq 0 \end{cases} \implies \partial_t C \geq 0 \quad (4)$$

and if for some $T > 0$

$$\liminf_{|x| \rightarrow \infty} \left(\inf_{0 \leq t \leq T} C(x, t) \right) \geq 0, \quad (5)$$

then

$$C(0, \cdot) \geq 0 \implies \forall t \in [0, T], C(t, \cdot) \geq 0.$$

This lemma is easily understood heuristically: if a local minimum of $C(t, \cdot)$ is equal to 0 at time t , then at this point $C = 0$, $\nabla C = 0$ and $\text{Hess}(C) \geq 0$, hence $\partial_t C \geq 0$. The minimum is "forced" to increase again, the graph of C cannot cross the x -axis. Moreover Condition (5) prevents C from becoming negative at infinity.

Proof. For $\varepsilon > 0$, set $C_\varepsilon(t, x) = C(t, x) + \varepsilon t$ on $[0, T] \times (\mathbb{R}^n)^m$. If $C_\varepsilon < 0$ at some point, then C_ε reaches its minimum at a point (t_0, x_0) where $\nabla C = 0$, $\text{Hess}(C) \geq 0$, $C < 0$ and $\partial_t C + \varepsilon \leq 0$ ($= 0$ if $t_0 < T$). By the hypotheses, it implies $\partial_t C \geq 0$ which is in contradiction with $\partial_t C \leq -\varepsilon$. So for all $\varepsilon > 0$ and $T > 0$, C_ε is non-negative on $[0, T] \times (\mathbb{R}^n)^m$, thus C is non-negative everywhere. \square

Property (5) is true under mild assumptions on f_i which are related to the initial condition $C(0, \cdot) \geq 0$ in the large:

Lemma 2. *If there exist $a_1, \dots, a_m \in \mathbb{R}$ such that*

- for $1 \leq i \leq m$, $\limsup_{|x| \rightarrow \infty} f_i(x) \leq \Phi(a_i)$

- $f_0 \geq \Phi(\sum \alpha_i a_i)$

then for all $T > 0$,

$$\liminf_{|x| \rightarrow \infty} \left(\inf_{0 \leq t \leq T} C(x, t) \right) \geq 0.$$

Proof. Let $\delta > 0$. By continuity of Φ^{-1} , there exists $\varepsilon > 0$ such that

$$\forall 1 \leq i \leq m, \quad \Phi^{-1}(\Phi(a_i) + 2\varepsilon) \leq a_i + \frac{\delta}{\sum \alpha_j}.$$

Let $r > 0$ such that $\gamma_n(r\mathbb{B}^n) = 1 - \varepsilon$. Then, for $i \geq 1$, $0 \leq t \leq T$,

$$\begin{aligned} P_t f_i(x_i) &= \int_{r\mathbb{B}^n} f_i(x_i + \sqrt{t}y) \gamma_n(dy) + \int_{(r\mathbb{B}^n)^c} f_i(x_i + \sqrt{t}y) \gamma_n(dy) \\ &\leq (1 - \varepsilon) \sup_{x_i + r\sqrt{t}\mathbb{B}^n} f_i + \varepsilon \sup f_i \\ &\leq \sup_{x_i + r\sqrt{T}\mathbb{B}^n} f_i + \varepsilon \\ &\leq \Phi(a_i) + 2\varepsilon \quad \text{for } |x_i| \text{ large enough.} \end{aligned}$$

Moreover $P_t f_0 \geq \Phi(\sum \alpha_i a_i)$ so for $|x|$ large enough and for $0 \leq t \leq T$, it holds $C(t, x) \geq -\delta$. As $\delta > 0$ was arbitrary, the proof is complete. \square

Checking Property (4) of Lemma 1 requires the following lemma:

Lemma 3. *Let $d \geq 2$, $\alpha_1, \dots, \alpha_m > 0$. Let k be an integer with $0 \leq k \leq m$ and*

$$\begin{aligned} \varphi : (\mathbb{S}^{d-1})^k \times (\mathbb{B}^d)^{m-k} &\rightarrow \mathbb{R}_+ \\ (v_1, \dots, v_m) &\mapsto |\sum \alpha_i v_i| \end{aligned}$$

Then the image of φ is the interval

$$J := \left[\max \left(\{0\} \cup \left\{ \alpha_j - \sum_{i \neq j} \alpha_i, 1 \leq j \leq k \right\} \right), \sum \alpha_i \right].$$

Proof. As φ is continuous on a compact connected set, $\text{Im}(\varphi) = [\min \varphi, \max \varphi]$. Plainly $|\sum \alpha_i v_i| \leq \sum \alpha_i$, with equality if $v_1 = \dots = v_m$ is a unit vector. So $\max \varphi = \sum_i \alpha_i$. For all $j \leq k$, since $|v_j| = 1$, the triangle inequality gives

$$\left| \sum \alpha_i v_i \right| \geq \alpha_j |v_j| - \sum_{i \neq j} \alpha_i |v_i| \geq \alpha_j - \sum_{i \neq j} \alpha_i.$$

Hence $\text{Im}(\varphi) \subset J$ and these two segments have the same upper bound. Next we deal with the lower bound. Let us consider a point (v_1, \dots, v_m) where φ achieves its minimum, and differentiate:

For $j \leq k$, v_j lies in the unit sphere. Applying Lagrange multipliers theorem to φ^2 with respect to v_j gives a real number λ_j such that,

$$\alpha_j \sum_i \alpha_i v_i = \lambda_j v_j. \tag{6}$$

For $j > k$, the j -th variable lives in \mathbb{B}^d . If $|v_j| < 1$ the minimum is achieved at an interior point and the full gradient on φ^2 with respect to the j -th variable is zero. Hence $\sum_i \alpha_i v_i = 0$. On the other hand if at the minimum $|v_j| = 1$, differentiating in the j -th variable only along the unit sphere gives again the existence of $\lambda_j \in \mathbb{R}$ such that (6) is verified.

Eventually, we face 2 cases:

1. Either $\sum \alpha_i v_i = 0$ and $\min \varphi = 0$. In this case, the triangle inequality gives $0 = |\sum \alpha_i v_i| \geq \alpha_j - \sum_{i \neq j} \alpha_i$ whenever $j \leq k$.
2. Or the v_i 's are colinear unit vectors and there exists a partition $S_+ \amalg S_- = \{1, \dots, m\}$ and a unit vector v such that

$$\min \varphi = \left| \sum_{S_+} \alpha_i v - \sum_{S_-} \alpha_i v \right| = \sum_{S_+} \alpha_i - \sum_{S_-} \alpha_i > 0.$$

Assume that S_+ contains 2 indices j and ℓ . Let e_1 and e_2 be 2 orthonormal vectors of \mathbb{R}^d and let us denote by $R(\theta)$ the rotation in the plane $\text{Vect}(e_1, e_2)$ of angle θ . The length of the vector

$\alpha_j R(\theta)e_1 + \alpha_\ell e_1$ is a decreasing and continuous function of $\theta \in [0, \pi]$. Denote by $U(\theta)$ the rotation in the plane $\text{Vect}(e_1, e_2)$ which maps this vector to $|\alpha_j R(\theta)e_1 + \alpha_\ell e_1|e_1$. Then

$$\alpha_j U(\theta)R(\theta)e_1 + \alpha_\ell U(\theta)e_1 + \sum_{S_+ \setminus \{j, \ell\}} \alpha_i e_1 - \sum_{S_-} \alpha_i e_1 = \lambda(\theta)e_1,$$

where $\lambda(0) = \sum_{S_+} \alpha_i - \sum_{S_-} \alpha_i = \min \varphi > 0$ and λ is continuous and decreasing in $\theta \in [0, \pi]$. This contradicts the minimality of $\min \varphi$. So S_+ contains a single index j and

$$\min \varphi = \left| \alpha_j v - \sum_{i \neq j} \alpha_i v \right| = \alpha_j - \sum_{i \neq j} \alpha_i > 0.$$

Note that necessarily $j \leq k$, otherwise one could get a shorter vector by replacing $v_j = v$ by $(1 - \varepsilon)v$. Besides, the condition $\alpha_j - \sum_{i \neq j} \alpha_i > 0$ ensures that $\alpha_j > \alpha_\ell$ for $\ell \neq j$. This implies that for $\ell \neq j$,

$$\alpha_\ell - \sum_{i \neq \ell} \alpha_i \leq \alpha_\ell - \alpha_j < 0 < \alpha_j - \sum_{i \neq j} \alpha_i.$$

So $\min \varphi = \max \left(\{0\} \cup \left\{ \alpha_j - \sum_{i \neq j} \alpha_i, 1 \leq j \leq k \right\} \right)$ as claimed. □

2.2 Semigroup proof for smooth functions

We deal with smooth functions f_i first, in order to ensure that $P_t f_i$ verifies the heat equation. This restrictive assumption will be removed in Section 3 where the proof of Theorem 1 is completed.

Theorem 2. *Let f_i be twice continuously differentiable functions from \mathbb{R}^n to $(0, 1)$ satisfying the hypotheses of Lemma 2. Assume that*

$$\forall t > 0, \forall x \in \mathbb{R}^n, \quad \left| \nabla f_i(x + \sqrt{t}y) \right| e^{-\frac{|y|^2}{2}} \xrightarrow{|y| \rightarrow \infty} 0.$$

Let $\alpha_1, \dots, \alpha_m$ be positive real numbers such that

$$\sum \alpha_i \geq 1 \quad \text{and} \quad \forall j, \alpha_j - \sum_{i \neq j} \alpha_i \leq 1.$$

If

$$\forall x_i \in \mathbb{R}^n, \quad \Phi^{-1} \circ f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ f_i(x_i),$$

then

$$\forall t \geq 0, \forall x_i \in \mathbb{R}^n, \quad \Phi^{-1} \circ P_t f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ P_t f_i(x_i).$$

Proof. Let us recall that C is defined by

$$C(t, x) = C(t, x_1, \dots, x_m) = F_0(t, \sum \alpha_i x_i) - \sum \alpha_i F_i(t, x_i)$$

where we have set

$$F_i(t, y) = \Phi^{-1} \circ P_t f_i(y).$$

In what follows, we omit the variables and write F_0 for $F_0(t, \sum \alpha_i x_i)$ and F_i instead of $F_i(t, x_i)$ when $i \geq 1$. With this simplified notation,

$$\begin{aligned} C &= F_0 - \sum \alpha_i F_i, \\ \nabla_{x_i} C &= \alpha_i (\nabla F_0 - \nabla F_i), \\ \nabla_{x_i} \nabla_{x_j}^* C &= \alpha_i \alpha_j \text{Hess}(F_0) - \delta_{ij} \alpha_i \text{Hess}(F_i). \end{aligned}$$

Moreover, one can use the property of heat kernel to derive a differential equation for each F_i . Indeed, for any f satisfying hypotheses of the theorem, we can perform an integration by parts so that it holds

$$\partial_t P_t f = \frac{1}{2} \Delta P_t f.$$

Then we set $F = \Phi^{-1} \circ P_t f$ and use the identity $(1/\Phi'(x))' = x/\Phi'(x)$ to show

$$\begin{aligned} \partial_t F &= \frac{\partial_t P_t f}{\Phi'(F)} = \frac{\Delta P_t f}{2\Phi'(F)}, \\ \nabla F &= \frac{\nabla P_t f}{\Phi'(F)}, \\ \Delta F &= \frac{\Delta P_t f}{\Phi'(F)} + F \frac{|\nabla P_t f|^2}{(\Phi'(F))^2}. \end{aligned}$$

We put all together to get

$$\partial_t F = \frac{1}{2} (\Delta F - F |\nabla F|^2)$$

and to deduce the following differential equation for C :

$$\partial_t C = \frac{1}{2} (\mathcal{S} + \mathcal{P})$$

where the second order part is

$$\mathcal{S} = \Delta F_0 - \sum \alpha_i \Delta F_i$$

and the terms of lower order are

$$\mathcal{P} = - \left(F_0 |\nabla F_0|^2 - \sum \alpha_i F_i |\nabla F_i|^2 \right).$$

We will conclude using Lemma 1. So we need to check Condition (4). First we note that \mathcal{P} is non-negative when $\nabla C = 0$ and $C \leq 0$, regardless of α . Indeed, $\nabla C = 0$ implies that $\nabla F_i = \nabla F_0$ for all $i \geq 1$. So $\mathcal{P} = -|\nabla F_0|^2 C$ which is non-negative if $C \leq 0$.

It remains to deal with the second order part. It is enough to express \mathcal{S} as $\mathcal{E}C$ for some elliptic operator \mathcal{E} , since then $\text{Hess}(C) \geq 0$ implies $\mathcal{S} \geq 0$. Such a second order operator can be written as $\mathcal{E} = \nabla^* A \nabla$ where A is a symmetric matrix $nm \times nm$. Moreover \mathcal{E} is elliptic if and only if A is semi-definite positive. In view of the structure of the problem, it is natural to look for semi-definite matrices of the following block form

$$A = B \otimes I_n = (b_{ij} I_n)_{1 \leq i, j \leq m},$$

where I_n is the identity $n \times n$ matrix and B is a semi-definite positive matrix of size m . Denoting $x_i = (x_{i,1}, \dots, x_{i,n})$,

$$\begin{aligned} \mathcal{E}C &= \sum_{i,j=1}^m b_{i,j} \left(\sum_{k=1}^n \frac{\partial^2}{\partial x_{i,k} \partial y_{j,k}} C \right) = \sum_{i,j=1}^m b_{i,j} (\alpha_i \alpha_j \Delta F_0 - \delta_{i,j} \alpha_i F_i) \\ &= \langle \alpha, B \alpha \rangle \Delta F_0 - \sum_{i=1}^m b_{i,i} \alpha_i \Delta F_i. \end{aligned}$$

Hence there exists an elliptic operator \mathcal{E} of the above form such that $\mathcal{E}C = \mathcal{S} = \Delta F_0 - \sum_{i=1}^m \alpha_i \Delta F_i$ if there exists a semi-definite positive matrix B of size m such that

$$\langle \alpha, B \alpha \rangle = \langle e_1, B e_1 \rangle = \dots = \langle e_m, B e_m \rangle = 1$$

where $(e_i)_i$ is the canonical basis of \mathbb{R}^m . Now a semi-definite positive matrix B can be decomposed into $B = V^*V$ where V is a square matrix of size m . Calling $v_1, \dots, v_m \in \mathbb{R}^m$ the columns of V , we can translate the latter into conditions on vectors v_i . Actually, we are looking for vectors $v_1, \dots, v_m \in \mathbb{R}^m$ with

$$|v_1| = \dots = |v_m| = \left| \sum \alpha_i v_i \right| = 1.$$

By Lemma 3 for $k = m$, this is possible exactly when α satisfies the claimed condition:

$$\sum \alpha_i \geq 1 \quad \text{and} \quad \forall j, \alpha_j - \sum_{i \neq j} \alpha_i \leq 1.$$

□

The following corollary will be useful in the next section.

Corollary 1. *Let f be a function on \mathbb{R}^n taking values in $(0, 1)$ and vanishing at infinity. Assume the same smoothness conditions as in Theorem 2. If $\Phi^{-1} \circ f$ is concave, then $\Phi^{-1} \circ P_t f$ is concave for all $t \geq 0$.*

Proof. Let $\varepsilon > 0$ and $\alpha_i > 0$ with $\sum \alpha_i = 1$. Choosing $f_0 = \varepsilon + (1 - \varepsilon)f \geq f$ and $f_i = f$ for $i \geq 1$, one can check that the latter theorem applies. Hence for all $t \geq 0$ and $x_i \in \mathbb{R}^n$:

$$\Phi^{-1} \circ P_t(\varepsilon + (1 - \varepsilon)f)(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ P_t f(x_i).$$

Letting ε go to 0, we get by monotone convergence that $\Phi^{-1} \circ P_t f$ is concave. □

2.3 Φ^{-1} -concave functions

When some of the f_i 's are Φ^{-1} -concave, the conditions on the parameters can be relaxed. Such functions allow to approximate characteristic functions of convex sets. They will be useful in Section 3.

Theorem 3. *Let $I_{conv} \subset \{1, \dots, m\}$. Let f_i be functions on \mathbb{R}^n taking values in $(0, 1)$ and satisfying the hypotheses of Lemma 2. Assume that they are twice continuously differentiable, with a gradient such that*

$$\forall t > 0, \forall x \in \mathbb{R}^n, \quad \left| \nabla f_i(x + \sqrt{t}y) \right| e^{-\frac{|y|^2}{2}} \xrightarrow{|y| \rightarrow \infty} 0.$$

Assume moreover that $\Phi^{-1} \circ f_i$ is concave, decreasing towards $-\infty$ at infinity for all $i \in I_{conv}$.

Let $\alpha_1, \dots, \alpha_m$ be positive numbers satisfying

$$\sum \alpha_i \geq 1 \quad \text{and} \quad \forall j \notin I_{conv}, \alpha_j - \sum_{i \neq j} \alpha_i \leq 1.$$

If

$$\forall x_i \in \mathbb{R}^n, \quad \Phi^{-1} \circ f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ f_i(x_i),$$

then

$$\forall t \geq 0, \forall x_i \in \mathbb{R}^n, \quad \Phi^{-1} \circ P_t f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ P_t f_i(x_i).$$

Proof. As in the proof of Theorem 2, we try to apply Lemma 1 to the equation satisfied by C :

$$\partial_t C(t, x) = \frac{1}{2}(\mathcal{S} + \mathcal{P}).$$

We have already shown that \mathcal{P} is non-negative when $\nabla C = 0$ and $C \leq 0$, for any $\alpha_1, \dots, \alpha_m$. We would like to prove that the conditions on α in the theorem imply that \mathcal{S} is non-negative whenever $\text{Hess}(C) \geq 0$.

By Corollary 1, for all $i \in I_{conv}$ the function F_i is concave, hence $\Delta F_i \leq 0$. So we are done if we can write

$$\mathcal{S} = \mathcal{E}C - \sum_{i \in I_{conv}} \lambda_i \Delta F_i,$$

for some elliptic operator \mathcal{E} and some $\lambda_i \geq 0$. As in the proof of the previous theorem, we are looking for operators of the form $\mathcal{E} = \nabla^* A \nabla$ with $A = B \otimes I_n = (b_{ij} I_n)_{1 \leq i, j \leq m}$ where B is a symmetric semi-definite positive matrix $m \times m$. Hence our task is to find $B \geq 0$ and $\lambda_i \geq 0$ such that $\lambda_i = 0$ when $i \notin I_{conv}$ and

$$\Delta F_0 - \sum \alpha_i \Delta F_i = \langle \alpha, B\alpha \rangle \Delta F_0 - \sum_i (b_{ii} \alpha_i + \lambda_i) \Delta F_i.$$

When $i \in I_{conv}$, we can find $\lambda_i \geq 0$ such that $b_{ii} \alpha_i + \lambda_i = \alpha_i$ whenever $b_{ii} \leq 1$. Consequently, the problem reduces to finding a semi-definite positive matrix B of size $m \times m$ such that

$$\begin{cases} \langle e_i, B e_i \rangle \leq 1, & \forall i \in I_{conv} \\ \langle e_i, B e_i \rangle = 1, & \forall i \notin I_{conv} \\ \langle \alpha, B \alpha \rangle = 1 \end{cases}$$

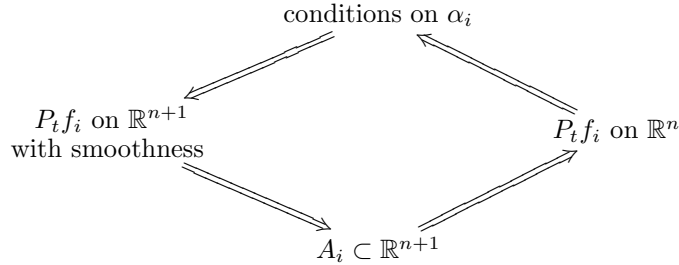
where $(e_i)_i$ is the canonical basis of \mathbb{R}^m . Equivalently, do there exist $v_1, \dots, v_m \in \mathbb{R}^m$ such that

$$\begin{cases} |v_i| \leq 1, & \forall i \in I_{conv} \\ |v_i| = 1, & \forall i \notin I_{conv} \\ |\sum \alpha_i v_i| = 1 \end{cases} \quad ?$$

We conclude with Lemma 3. □

3 Back to sets

This sections explains how to complete the proof of Theorem 1. The main issue is to get rid of the smoothness assumptions that we made so far. The plan of the argument is summed up in the next figure. The key point is that the conditions on α do not depend on n .



“conditions on $\alpha_i \Rightarrow P_t f_i$ on \mathbb{R}^{n+1} with smoothness”: This implication is nothing else than Theorem 3. Equivalently, the first assertion in Theorem 1 implies the fourth one restricted to “smooth” functions (i.e. verifying all the assumptions of the first paragraph of Theorem 3).

“ $P_t f_i$ on \mathbb{R}^n with smoothness $\Rightarrow A_i \subset \mathbb{R}^{n+1}$ ”: For arbitrary α , let us prove that the fourth assertion in Theorem 1 restricted to smooth functions (in the above-mentioned sense) implies the second assertion of the theorem, involving sets. Let A_1, \dots, A_m be Borel sets in \mathbb{R}^n with A_i convex when $i \in I_{conv}$. By inner regularity of the measure, we can assume that they are compact. Let $\varepsilon > 0$ and $b > a$ be fixed. Then,

- for $i \notin I_{conv}$: there exists a smooth function f_i such that $f_i = \Phi(b)$ on A_i , $f_i = \Phi(a)$ off A_i^ε and $0 < \Phi(a) \leq f_i \leq \Phi(b) < 1$.

- for $i \in I_{conv}$: there exists a smooth function f_i such that $F_i = \Phi^{-1} \circ f_i$ is concave, $F_i = b$ on A_i , $F_i \leq a$ off A_i^ε and $F_i \leq b$ on \mathbb{R}^n .

For instance, take a point x_i in A_i and define the gauge of $A_i^{\varepsilon/3}$ with respect to x_i by

$$\rho(x) = \inf \left\{ \lambda > 0, x_i + \frac{1}{\lambda}(x - x_i) \in A_i^{\varepsilon/3} \right\}.$$

We know that ρ is convex since A_i is convex (see for instance [22]). Then set

$$\tilde{F}_i(x) = b + c \left(1 - \max(\rho(x), 1) \right)$$

where $c > 0$ is chosen large enough to insure that $\tilde{F}_i \leq a$ off $A_i^{2\varepsilon/3}$. Now, we can take a smooth function g with compact support small enough and of integral 1, such that $f_i = \Phi^{-1}(\tilde{F}_i * g)$ is a smooth Φ^{-1} -concave function satisfying the required conditions.

- for $i = 0$: set

$$a_0 = \max_{\substack{u_i = a \text{ or } b \\ u \neq (b, \dots, b)}} \sum \alpha_i u_i \quad \text{and} \quad b_0 = \sum \alpha_i b.$$

Again, we can choose a smooth function f_0 such that $f_0 = \Phi(b_0)$ on $\sum \alpha_i A_i^\varepsilon$, $f_0 = \Phi(a_0)$ off $(\sum \alpha_i A_i^\varepsilon)^\varepsilon$ and $0 < \Phi(a_0) \leq f_0 \leq \Phi(b_0) < 1$.

From these definitions, the functions f_i are “smooth” and satisfy

$$\forall x_i \in \mathbb{R}^n, \quad \Phi^{-1} \circ f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ f_i(x_i).$$

By our hypothesis, the inequality remains valid with $P_t f_i$ instead of f_i for all $t > 0$. Choosing $t = 1$, $x_i = 1$ yields

$$\Phi^{-1} \left(\int f_0 d\gamma_n \right) \geq \sum \alpha_i \Phi^{-1} \left(\int f_i d\gamma_n \right).$$

Letting first $a \rightarrow -\infty$ and then $b \rightarrow +\infty$, $\varepsilon \rightarrow 0$, we obtain that

$$\Phi^{-1} \circ \gamma_n(\sum \alpha_i A_i) \geq \sum \alpha_i \Phi^{-1} \circ \gamma_n(A).$$

“ $A_i \subset \mathbb{R}^{n+1} \Rightarrow P_t f_i$ on \mathbb{R}^n ”. Here we assume that the second assumption of Theorem 1 is valid for all Borel sets in \mathbb{R}^{n+1} and we derive the fourth assumption of the theorem for functions defined on \mathbb{R}^n .

For any Borel function f on \mathbb{R}^n taking values in $[0, 1]$, $t > 0$ and $x \in \mathbb{R}^n$, we define

$$B_f^{t,x} = \left\{ (u, y) \mid u \leq \Phi^{-1} \circ f(x + \sqrt{t}y) \right\} \subset \mathbb{R} \times \mathbb{R}^n.$$

Then it holds

$$\gamma_{n+1}(B_f^{t,x}) = P_t f(x).$$

Let f_0, \dots, f_n be Borel functions on \mathbb{R}^n with values in $[0, 1]$, such that $\Phi^{-1} \circ f_i$ is concave when $i \in I_{conv}$. Assume that

$$\forall x_i \in \mathbb{R}^n, \quad \Phi^{-1} \circ f_0(\sum \alpha_i x_i) \geq \sum \alpha_i \Phi^{-1} \circ f_i(x_i).$$

Then for (u_i, y_i) in $B_{f_i}^{t,x_i}$, we get

$$\sum \alpha_i u_i \leq \sum \alpha_i \Phi^{-1} \circ f_i(x_i + \sqrt{t}y_i) \leq \Phi^{-1} \circ f_0(\sum \alpha_i (x_i + \sqrt{t}y_i))$$

which means that

$$\sum \alpha_i B_{f_i}^{t, x_i} \subset B_{f_0}^{t, \sum \alpha_i x_i}.$$

The same argument shows that $B_f^{t, x}$ is convex if $\Phi^{-1} \circ f$ is concave. Thus, the result for sets in \mathbb{R}^{n+1} implies that

$$\Phi^{-1} \circ P_t f_0(\sum \alpha_i x_i) \geq \Phi^{-1} \circ \gamma_{n+1} \left(\sum \alpha_i B_{f_i}^{t, x_i} \right) \geq \sum \alpha_i \Phi^{-1} \circ P_t f_i(x_i).$$

“ $P_t f_i$ on $\mathbb{R}^n \Rightarrow$ conditions on α_i ”: We will prove the contraposed assertion: if the conditions on α_i are violated, then there exists functions f_i such that $\Phi^{-1} \circ f_i$ is concave for $i \in I_{conv}$, which verify for all x_i the relation $\Phi^{-1} \circ f_0(\sum \alpha_i x_i) \geq \sum \Phi^{-1} \circ f_i(x_i)$ but for which this inequality is not preserved by P_t for some t . Actually since $P_1 f(0) = \int f d\gamma$, it will be enough to exhibit functions such that

$$\Phi^{-1} \left(\int f_0 d\gamma \right) < \sum_{i=1}^m \Phi^{-1} \left(\int f_i d\gamma \right).$$

Let $f : \mathbb{R}^n \rightarrow (0, 1)$ be an even Borel function such that

$$f(0) > \frac{1}{2}, \quad \int f d\gamma < \frac{1}{2} \quad \text{and} \quad F = \Phi^{-1} \circ f \quad \text{is concave.}$$

For instance, we may take $f(x) = \Phi(1 - |ax|^2)$ for a large enough. Note that for $0 \leq t \leq 1$,

$$F(tx) \geq tF(x) + (1-t)F(0) \geq tF(x). \tag{7}$$

Assume first that $\sum \alpha_i < 1$. Then by concavity and the latter bound, we get for all x_i ,

$$\begin{aligned} \Phi^{-1} \circ f(\sum_i \alpha_i x_i) &= F(\sum_i \alpha_i x_i) \geq \sum_i \frac{\alpha_i}{\sum_j \alpha_j} F\left(\left(\sum_j \alpha_j\right) x_i\right) \\ &\geq \sum_i \alpha_i F(x_i) = \sum_i \alpha_i \Phi^{-1} \circ f(x_i). \end{aligned}$$

However since $1 > \sum \alpha_i$ and $\Phi^{-1}(\int f d\gamma) < 0$, it holds

$$\Phi^{-1} \left(\int f d\gamma \right) < \sum_i \alpha_i \Phi^{-1} \left(\int f d\gamma \right).$$

Assume now that there exists $j \notin I_{conv}$ such that $\alpha_j - \sum_{i \neq j} \alpha_i > 1$. Then using (7) and concavity again, we obtain for all x_i ,

$$\alpha_j F(x_j) \geq \left(1 + \sum_{i \neq j} \alpha_i\right) F\left(\frac{\alpha_j x_j}{1 + \sum_{i \neq j} \alpha_i}\right) \geq F\left(\alpha_j x_j - \sum_{i \neq j} \alpha_i x_i\right) + \sum_{i \neq j} \alpha_i F(x_i).$$

Let $g = 1 - f$. Since $-F = -\Phi^{-1} \circ f = \Phi^{-1} \circ (1 - f) = \Phi^{-1} \circ g$ and f is even we may rewrite the latter as

$$\Phi^{-1} \circ g\left(\alpha_j x_j + \sum_{i \neq j} \alpha_i (-x_i)\right) \geq \alpha_j \Phi^{-1} \circ g(x_j) + \sum_{i \neq j} \alpha_i \Phi^{-1} \circ f(-x_i).$$

However, since $\Phi^{-1}(\int g d\gamma) = -\Phi^{-1}(\int f d\gamma) > 0$ and $\alpha_j - \sum_{i \neq j} \alpha_i > 1$ it also holds

$$\Phi^{-1} \left(\int g d\gamma \right) < \alpha_j \Phi^{-1} \left(\int g d\gamma \right) + \sum_{i \neq j} \alpha_i \Phi^{-1} \left(\int f d\gamma \right).$$

Therefore the proof is complete.

4 Further remarks

4.1 Brascamp-Lieb type inequalities

In the previous papers [8, 9], Borell already used his semigroup approach to derive variants of the Prékopa-Leindler inequality. The later is a functional counterpart to the Brunn-Minkowski inequality for the Lebesgue measure and reads as follows: if $\lambda \in (0, 1)$ and $f, g, h : \mathbb{R}^n \rightarrow \mathbb{R}^+$ are Borel functions such that for all $x, y \in \mathbb{R}^n$,

$$h(\lambda x + (1 - \lambda)y) \geq f(x)^\lambda g(y)^{1-\lambda}$$

then $\int h \geq (\int f)^\lambda (\int g)^{1-\lambda}$ where the integrals are with respect to Lebesgue's measure. Borell actually showed the following stronger fact: for all $t > 0$ and all $x, y \in \mathbb{R}^n$

$$P_t h(\lambda x + (1 - \lambda)y) \geq P_t f(x)^\lambda P_t g(y)^{1-\lambda}.$$

Setting $H(t, \cdot) = \log P_t h$ and defining F, G similarly, it is proved that $C(t, x, y) := H(t, \lambda x + (1 - \lambda)y) - \lambda F(t, x) + (1 - \lambda)G(t, y)$ satisfies a positivity-preserving evolution equation. The argument is simpler than for Ehrhard's inequality since the evolution equation of individual functions is simpler: $2\partial_t H = \Delta H + |\nabla H|^2$.

The Brascamp-Lieb [14, 20] inequality is a powerful extension of Hölder's inequality. The so-called reverse Brascamp-Lieb inequality, first proved in [2, 3], appears as an extension of the Prékopa-Leindler inequality. In the paper [4], it was noted that Borell's semigroup method could be used to derive the geometric reverse Brascamp-Lieb inequality (which in some sense is a generic case, see [6]) for functions of one variable. This observation was also motivated by a proof of the Brascamp-Lieb inequalities based on semigroup techniques (Carlen Lieb and Loss [16] for functions of one variable, and Bennett Carbery Christ and Tao [6] for general functions). In this subsection, we take advantage of our streamlined presentation of Borell's method, and quickly reprove the reverse Brascamp-Lieb inequality in geometric form, but for functions of several variables. More surprisingly we will recover the Brascamp-Lieb from inequalities which are preserved by the Heat flow. The result is not new (the inequality for the law of the semigroup appears in the preprint [5]), but it is interesting to have semigroup proofs of the direct and of the reverse inequalities which follow exactly the same lines. Recall that the transportation argument developed in [3] was providing the direct and the reverse inequality simultaneously.

The setting of the geometric inequalities is as follows: for $i = 1, \dots, m$ let $c_i > 0$ and let $B_i : \mathbb{R}^N \rightarrow \mathbb{R}^{n_i}$ be linear maps such that $B_i B_i^* = I_{n_i}$ and

$$\sum_{i=1}^m c_i B_i^* B_i = I_N. \quad (8)$$

These hypotheses were put forward by Ball in connection with volume estimates in convex geometry [1]. Note that B_i^* is an isometric embedding of \mathbb{R}^{n_i} into \mathbb{R}^N and that $B_i^* B_i$ is the orthogonal projection from \mathbb{R}^N to $E_i = \text{Im}(B_i^*)$. The Brascamp-Lieb inequality asserts that for all Borel functions $f_i : \mathbb{R}^{n_i} \rightarrow \mathbb{R}^+$ it holds

$$\int_{\mathbb{R}^N} \prod_{i=1}^m f_i(B_i x)^{c_i} dx \leq \prod_{i=1}^m \left(\int_{\mathbb{R}^{n_i}} f_i \right)^{c_i}.$$

The reverse inequality ensures that

$$\int_{\mathbb{R}^N}^* \sup \left\{ \prod_{i=1}^m f_i(x_i)^{c_i}; x_i \in \mathbb{R}^{n_i} \text{ with } \sum c_i B_i^* x_i = x \right\} dx \geq \prod_{i=1}^m \left(\int_{\mathbb{R}^{n_i}} f_i \right)^{c_i}.$$

Following [4], we will deduce the later from the following result:

Theorem 4. *If $h : \mathbb{R}^N \rightarrow \mathbb{R}^+$ and $f_i : \mathbb{R}^{n_i} \rightarrow \mathbb{R}^+$ satisfy $\forall x_i \in \mathbb{R}^{n_i}$,*

$$h\left(\sum_{i=1}^m c_i B_i^* x_i\right) \geq \prod_{i=1}^m f_i(x_i)^{c_i}$$

then $\forall x_i \in \mathbb{R}^{n_i}$,

$$P_t h \left(\sum_{i=1}^m c_i B_i^* x_i \right) \geq \prod_{i=1}^m P_t f_i(x_i)^{c_i}.$$

The reverse inequality is obtained as $t \rightarrow +\infty$ since for f on \mathbb{R}^d , $P_t f(x)$ is equivalent to $(2\pi t)^{-d/2} \int_{\mathbb{R}^d} f$. Note that taking traces in the decomposition of the identity map yields $\sum_i c_i n_i = N$.

In order to recover the Brascamp-Lieb inequality, we will show the following:

Theorem 5. *If $h : \mathbb{R}^N \rightarrow \mathbb{R}^+$ and $f_i : \mathbb{R}^{n_i} \rightarrow \mathbb{R}^+$ satisfy $\forall x \in \mathbb{R}^N$,*

$$h(x) \leq \prod_{i=1}^m f_i(B_i x)^{c_i},$$

then $\forall x \in \mathbb{R}^N$,

$$P_t h(x) \leq \prod_{i=1}^m P_t f_i(B_i x)^{c_i}.$$

Again, the limit $t \rightarrow +\infty$ yields the inequality when choosing $h(x) = \prod_{i=1}^m f_i(B_i x)^{c_i}$. We sketch the proofs of the above two statements, omitting the truncation arguments needed to ensure Condition (5).

Proof of Theorem 4. Set $H(t, \cdot) = \log P_t h(\cdot)$ and $F_i(t, \cdot) = \log P_t f_i(\cdot)$. They evolve according to $2\partial_t H = \Delta H + |\nabla H|^2$. Set for $(t, x_1, \dots, x_m) \in \mathbb{R}^+ \times \mathbb{R}^{n_1} \times \dots \times \mathbb{R}^{n_m}$

$$C(t, x_1, \dots, x_m) := H \left(t, \sum_{i=1}^m c_i B_i^* x_i \right) - \sum_{i=1}^m c_i F_i(t, x_i).$$

By hypothesis $C(0, \cdot) \geq 0$ and we want to prove that $C(t, \cdot)$ is non-negative as well. As before, we are done if we can show that the three conditions $C \leq 0$, $\nabla C = 0$ and $\text{Hess}(C) \geq 0$ imply that $\partial_t C \geq 0$. Omitting variables,

$$2\partial_t C = \left(\Delta H - \sum c_i \Delta F_i \right) + \left(|\nabla H|^2 - \sum c_i |\nabla F_i|^2 \right) =: \mathcal{S} + \mathcal{P},$$

so that the condition $C \leq 0$ will not be used. Straightforward calculations give

$$\nabla_{x_i} C = c_i B_i \nabla H - c_i \nabla F_i \quad \text{and} \quad \text{Hess}_{x_i, x_j}(C) = c_i c_j B_i \text{Hess}(H) B_j^* - \delta_{i,j} c_i \text{Hess}(F_i).$$

Note that the decomposition (8) implies for all $v \in \mathbb{R}^N$

$$|v|^2 = \langle v, \sum c_i B_i^* B_i v \rangle = \sum c_i |B_i v|^2.$$

Hence, if $\nabla C = 0$, the above calculation gives $\nabla F_i = B_i \nabla H$. Consequently $|\nabla H|^2 = \sum c_i |B_i \nabla H|^2 = \sum c_i |\nabla F_i|^2$. So $\nabla C = 0 \implies \mathcal{P} = 0$.

Next, we deal with the second order term. Using (8) again

$$\begin{aligned} \Delta H &= \text{Tr}(\text{Hess}(H)) = \text{Tr} \left(\left(\sum_i c_i B_i^* B_i \right) \text{Hess}(H) \left(\sum_j c_j B_j^* B_j \right) \right) \\ &= \sum_{i,j} \text{Tr} \left(B_i^* (c_i c_j B_i \text{Hess}(H) B_j^*) B_j \right) \end{aligned}$$

Also note that

$$\begin{aligned} \sum_{i,j} \text{Tr} \left(B_i^* (\delta_{i,j} c_i \text{Hess}(F_i)) B_j \right) &= \sum_i \text{Tr} (B_i^* c_i \text{Hess}(F_i) B_i) = \sum_i c_i \text{Tr} (\text{Hess}(F_i) B_i B_i^*) \\ &= \sum_i c_i \Delta F_i, \end{aligned}$$

since $B_i B_i^* = I_{n_i}$. Combining the former and the later and denoting by J_i the canonical embedding of \mathbb{R}^{n_i} into $\mathbb{R}^{n_1 + \dots + n_m}$ we get that

$$\begin{aligned} \mathcal{S} &= \Delta H - \sum c_i \Delta F_i = \sum_{i,j} \text{Tr}(B_i^* \text{Hess}_{x_i, x_j}(C) B_j) \\ &= \sum_{i,j} \text{Tr}\left(B_i^* (J_i^* \text{Hess}(C) J_j) B_j\right) = \text{Tr}\left(\left(\sum_i J_i B_i\right)^* \text{Hess}(C) \left(\sum_j J_j B_j\right)\right) \end{aligned}$$

is non-negative when $\text{Hess}(C) \geq 0$. This is enough to conclude that C remains non-negative. \square

Proof of Theorem 5. As before we set $H(t, \cdot) = \log P_t h(\cdot)$ and $F_i(t, \cdot) = \log P_t f_i(\cdot)$. For $(t, x) \in \mathbb{R}^+ \times \mathbb{R}^N$

$$C(t, x) := \sum_{i=1}^m c_i F_i(t, B_i x) - H(t, x).$$

Omitting variables, C evolves according to the equation

$$\partial_t C = \left(\sum c_i \Delta F_i - \Delta H\right) + \left(\sum c_i |\nabla F_i|^2 - |\nabla H|^2\right) =: \mathcal{S} + \mathcal{P}.$$

Next

$$\nabla C = \sum c_i B_i^* \nabla F_i - \nabla H \quad \text{and} \quad \text{Hess}(C) = \sum c_i B_i^* \text{Hess}(F_i) B_i - \text{Hess}(H).$$

Taking traces in the later equality and since $B_i B_i^* = I_{n_i}$ we obtain

$$\Delta C = \sum_i c_i \text{Tr}\left(\text{Hess}(F_i) B_i B_i^*\right) - \Delta H = \sum_i c_i \Delta F_i - \Delta H = \mathcal{S}.$$

Therefore the second order term is clearly elliptic.

It remains to check that $\nabla C = 0$ implies that the first order term \mathcal{P} is non-negative. We will need the following easy consequence of the decomposition (8): if $x_i \in \mathbb{R}^{n_i}$, $i = 1, \dots, m$, then

$$\left| \sum c_i B_i^* x_i \right|^2 \leq \sum c_i |x_i|^2.$$

The proof is easy: set $v = \sum c_i B_i^* x_i$. Then by Cauchy-Schwarz

$$\begin{aligned} |v|^2 &= \left\langle v, \sum c_i B_i^* x_i \right\rangle = \sum c_i \langle B_i v, x_i \rangle \\ &\leq \left(\sum c_i |B_i v|^2 \right)^{\frac{1}{2}} \left(\sum c_i |x_i|^2 \right)^{\frac{1}{2}}. \end{aligned}$$

But (8) ensures that $|v|^2 = \sum c_i |B_i v|^2$ so after simplification we get the claim. Finally, note that $\nabla C = 0$ means that $\nabla H = \sum c_i B_i^* \nabla F_i$. Hence $|\nabla H|^2 \leq \sum c_i |\nabla F_i|^2$. In other words $\mathcal{P} \geq 0$. The proof is therefore complete. \square

4.2 Looking for Gaussian Brascamp-Lieb inequalities

It is natural to ask about Gaussian versions of the Brascamp-Lieb or inverse Brascamp-Lieb inequalities. For $0 \leq i \leq m$, take a nonzero real d_i , a positive integer $n_i \leq N$, a linear surjective map $L_i : \mathbb{R}^N \rightarrow \mathbb{R}^{n_i}$ and a Borel function f_i on \mathbb{R}^{n_i} taking value in $(0, 1)$. Does the inequality

$$\forall x \in \mathbb{R}^N, \quad \sum_{i=0}^m d_i \Phi^{-1} \circ f_i(L_i x) \geq 0$$

upgrade for all $t \geq 0$ to

$$\forall x \in \mathbb{R}^N, \quad \sum_{i=0}^m d_i \Phi^{-1} \circ P_t f_i(L_i x) \geq 0 \quad ?$$

This general formulation allows negative d_i 's and would encompass Gaussian extensions of Theorem 4 or Theorem 5. It also enables a better understanding of the essential properties in the semigroup argument.

As before, we define for $t \geq 0$ and $x \in \mathbb{R}^N$,

$$C(t, x) = \sum_{i=0}^m d_i \Phi^{-1} \circ P_t f_i(L_i x) = \sum d_i F_i(t, L_i x)$$

and we are interested in proving that $C(0, \cdot) \geq 0$ implies $C(t, \cdot) \geq 0$ for all $t \geq 0$. Assume that our functions are smooth enough for the next calculations. It holds

$$\begin{aligned} C &= \sum d_i F_i, \\ \nabla C &= \sum d_i L_i^* \nabla F_i, \\ \text{Hess}(C) &= \sum d_i L_i^* \text{Hess}(F_i) L_i, \end{aligned}$$

and thanks to the Heat equation, C satisfies the following differential equation $2\partial_t C = (\mathcal{S} + \mathcal{P})$ where

$$\mathcal{S} = \sum d_i \Delta F_i \text{ and } \mathcal{P} = - \sum d_i |\nabla F_i|^2 F_i.$$

We require that

$$\begin{cases} \text{Hess}(C) \geq 0 \\ \nabla C = 0 \\ C \leq 0 \end{cases} \implies \begin{cases} \mathcal{P} \geq 0 \\ \mathcal{S} \geq 0 \end{cases}$$

in order to apply Lemma 1 (the condition at infinity is verified, provided one restricts to good enough functions f_i . We omit the details). This request will translate in terms of conditions on the data (d_i, L_i) . We deal separately with the condition for each order:

First order terms : as F_i and ∇F_i can be chosen arbitrarily, the condition $(C \leq 0, \nabla C = 0) \implies \mathcal{P} \geq 0$ boils down to the following relation between polynomials

$$\begin{cases} \sum d_i Z_i \leq 0 \\ \sum d_i L_i^* Y_i = 0 \end{cases} \implies \sum d_i |Y_i|^2 Z_i \leq 0$$

where Z_i is a 1-dimensional unknown and Y_i is a n_i -dimensional one. Reasoning for fixed Y_i 's, and viewing the conditions on Z_i as equations of half-spaces, we easily see that the later condition is equivalent to

$$\sum d_i L_i^* Y_i = 0 \implies |Y_0|_{\mathbb{R}^{n_0}}^2 = \dots = |Y_m|_{\mathbb{R}^{n_m}}^2. \quad (9)$$

This condition can be worked out a bit more. Let $\mathcal{L} : \mathbb{R}^{\sum n_j} \rightarrow \mathbb{R}^N$ be defined by

$$\mathcal{L}(Y_0, \dots, Y_m) = \sum_i d_i L_i^* Y_i.$$

If $a = (a_0, \dots, a_m)$ and $b = (b_0, \dots, b_m)$ belong to $\ker \mathcal{L}$ then $|a_i|^2, |b_i|^2$ and by linearity $|a_i + b_i|^2$ are independent of i . Expanding the square of the sum, we deduce that $\langle a_i, b_i \rangle$ is independent of i and therefore equal to the average over i of these quantities. Hence for all i , $(m+1)\langle a_i, b_i \rangle = \langle a, b \rangle$. This means that $u_i : \ker \mathcal{L} \rightarrow \mathbb{R}^{n_i}$ defined by $u_i(a) = \sqrt{m+1} a_i$ is an isometry. Since $a_i = u_i(u_0^{-1}(a_0))$, we conclude that

$$\ker \mathcal{L} = \left\{ \left(a_0, u_1(u_0^{-1}(a_0)), \dots, u_m(u_0^{-1}(a_0)) \right); a_0 \in \text{Im}(u_0) \right\}.$$

It is then clear that Condition (9) is equivalent to the following: there exists a subspace $X \subset \mathbb{R}^{n_0}$ and linear isometries $R_i : X \rightarrow \mathbb{R}^{n_i}$, $i \geq 1$ such that

$$\ker \mathcal{L} = \{(x, R_1x, \dots, R_mx); x \in X\}. \quad (10)$$

Second order terms : we are done if we can find an elliptic operator \mathcal{E} such that $\mathcal{S} = \mathcal{E}C$. In other words we are looking for a symmetric semi-definite positive matrix A of size $N \times N$ such that the quantity

$$\text{Tr}(A \text{Hess}(C)) = \sum d_i \text{Tr}(AL_i^* \text{Hess}(F_i)L_i)$$

coincides with $\mathcal{S} = \sum d_i \Delta F_i$. As we require this identity for arbitrary functions F_i , we can conclude that A does the job if and only if for all $0 \leq i \leq m$,

$$L_i AL_i^* = I_{n_i}.$$

Eventually, we may look for A in the form $A = \sigma^* \sigma$ for some square matrix σ of size N . For $0 \leq i \leq m$ and $1 \leq j \leq n_i$, denote by $u_i^j \in \mathbb{R}^N$ the columns of L_i^* . Rewriting the later conditions in terms of σ we may conclude that: $\text{Hess}(C) \geq 0 \implies \mathcal{S} \geq 0$ holds provided there exists a matrix σ of size N such that for all $i \leq m$ the vectors $(\sigma u_i^j)_{j=1}^{n_i}$ form an orthonormal system in \mathbb{R}^N . Note that the first order condition requires that the linear relations between the vector u_i^j should have a particular structure.

The above conditions are quite restrictive. We were able to find data (d_i, L_i) verifying them, but all of them could be reduced to the Borell theorem, using the rotation invariance of the Gaussian measure and the fact that its marginals remain Gaussian. To conclude this section let us briefly explain why the method does not allow any new Gaussian improvement of Theorems 4 or 5.

For $i = 1, \dots, m$, let $c_i > 0$ and $B_i : \mathbb{R}^n \rightarrow \mathbb{R}^{n_i}$ be linear surjective maps. If we look for Gaussian versions of the Brascamp-Lieb inequality, we are led to apply the previous reasoning to $N = n$, $B_0 = I_N$, $d_0 = -1$ and for $i \geq 1$, $L_i = B_i$ and $d_i = c_i$. Now, with the above notation, $(Y_0, \dots, Y_m) \in \ker \mathcal{L}$ is equivalent to $Y_0 = \sum_{i=1}^m c_i B_i^* Y_i$. Since this condition can be verified even though $|Y_1| \neq |Y_2|$ we conclude that the first order condition is never satisfied.

Next, we are looking for inequalities of the reverse Brascamp-Lieb type. Hence we choose $N = n_1 + \dots + n_m$, $d_0 = 1$, $L_0(x_1, \dots, x_m) = \sum c_i B_i^* x_i$ and for $i \geq 1$, $d_i = -c_i$, $L_i(x_1, \dots, x_m) = x_i$. For $x \in \mathbb{R}^n$, $L_0^*(x) = (c_1 B_1 x, \dots, c_m B_m x)$. For $i \geq 1$ and $x_i \in \mathbb{R}^{n_i}$, $L_i^*(x_i) = (0, \dots, 0, x_i, 0, \dots, 0)$ where x_i appears at the i -th place. The condition $(Y_0, \dots, Y_m) \in \ker \mathcal{L}$, that is $L_0^*(Y_0) = \sum_{i \geq 1} c_i L_i^*(Y_i)$ becomes:

$$\forall i = 1, \dots, m, Y_i = B_i Y_0.$$

Hence $\ker \mathcal{L} = \{(Y_0, B_1 Y_0, \dots, B_m Y_0); Y_0 \in \mathbb{R}^n\}$. So the first order condition (10) is verified only if the B_i 's are isometries. This forces $n_i = n$ and up to an isometric change of variables, we are back to the setting of the Gaussian Brunn-Minkowski inequality.

4.3 No extension to $e^{|x|^2} dx$

In [7], Borell showed that origin-centered balls solve the isoperimetric problem for the measure $\eta_n(dx) = e^{|x|^2} dx$, $x \in \mathbb{R}^n$. More precisely, if $\eta_n(A) = \eta_n(a\mathbb{B}^n)$, then

$$\eta_n(A^\varepsilon) \geq \eta_n((a\mathbb{B}^n)^\varepsilon).$$

Setting $\Psi_n(a) := \eta_n(a\mathbb{B}^n)$, the latter inequality can be restated as:

$$\eta_n(A^\varepsilon) \geq \Psi_n(\Psi_n^{-1} \circ \eta_n(A) + \varepsilon).$$

For Lebesgue's measure and for the standard Gaussian measure, the sharp Brunn-Minkowski inequality formally implies the isoperimetric inequality. This lead Borell to ask in [11] whether a Brunn-Minkowski

type inequality holds for η_n , which would recover the above isoperimetric inequality. Such an inequality should be of the form:

$$\Psi_n^{-1} \circ \eta_n(\alpha A + \beta B) \geq \alpha \Psi_n^{-1} \circ \eta_n(A) + \beta \Psi_n^{-1} \circ \eta_n(B).$$

However such an inequality cannot hold without additional conditions. Indeed, if we apply the previous inequality to small balls around arbitrary points and let tend their (common) radius go to 0, we get

$$(\alpha + \beta)e^{\frac{1}{n}(\alpha x + \beta y)^2} \geq \alpha e^{\frac{1}{n}x^2} + \beta e^{\frac{1}{n}y^2}.$$

If $\alpha > 0$, $\beta > 0$, we can choose x and y satisfying the relation $\alpha x + \beta y = 0$ and we get a contradiction when x tends to infinity.

Remark. Let us finally point out the inequality $\Psi_n^{-1}(\eta_n(tA)) \geq t\Psi_n^{-1}(\eta_n(A))$ valid for $t \geq 1$ and arbitrary $A \subset \mathbb{R}^n$. It means that among sets of given measure, centered balls have dilates of minimal measure. The proof is short: we note that

$$\eta_n(tA) = \int_A t^n e^{t^2 x^2} dx = \int_A t^n e^{(t^2-1)x^2} d\eta_n(x)$$

and use the easy fact that for any measure μ , any non-negative function f and any $t \geq 0$.

$$\mu(A) = \mu(\{f \leq t\}) \implies \int_A f d\mu \geq \int_{\{f \leq t\}} f d\mu.$$

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