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Partitions and functional Santaló inequalities

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Abstract

We give a direct proof of a functional Santaló inequality due to Fradelizi and Meyer. This provides a new proof of the Blaschke-Santaló inequality. The argument combines a logarithmic form of the Prékopa-Leindler inequality and a partition theorem of Yao and Yao.

Introduction

If A is a subset of \mathbb{R}^n we let A° be the polar of A :

$$A^\circ = \{x \in \mathbb{R}^n \mid \forall y \in A, x \cdot y \leq 1\},$$

where $x \cdot y$ denotes the scalar product of x and y . We denote the Euclidean norm of x by $|x| = \sqrt{x \cdot x}$. Let K be a subset of \mathbb{R}^n with finite measure. The Blaschke-Santaló inequality states that there exists a point z in \mathbb{R}^n such that

$$\text{vol}_n(K) \text{vol}_n(K - z)^\circ \leq \text{vol}_n(B_2^n) \text{vol}_n(B_2^n)^\circ = v_n^2, \quad (1)$$

where vol_n stands for the Lebesgue measure on \mathbb{R}^n , B_2^n for the Euclidean ball and v_n for its volume. It was first proved by Blaschke in dimension 2 and 3 and Santaló [7] extended the result to any dimension. We say that an element z of \mathbb{R}^n satisfying (1) is a *Santaló point* for K .

Throughout the paper a *weight* is a measurable function $\rho : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ such that for any n , the function $x \in \mathbb{R}^n \mapsto \rho(|x|)$ is integrable.

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Definition 1. Let f be a non-negative integrable function on \mathbb{R}^n , and ρ be a weight. We say that $c \in \mathbb{R}^n$ is a Santaló point for f with respect to ρ if the following holds: for all non-negative Borel function g on \mathbb{R}^n , if

$$\forall x, y \in \mathbb{R}^n, \quad x \cdot y \geq 0 \Rightarrow f(c+x)g(y) \leq \rho(\sqrt{x \cdot y})^2, \quad (2)$$

then

$$\int_{\mathbb{R}^n} f(x) dx \int_{\mathbb{R}^n} g(y) dy \leq \left(\int_{\mathbb{R}^n} \rho(|x|) dx \right)^2. \quad (3)$$

Heuristically, the choice of the weight ρ gives a notion of duality (or polarity) for non-negative functions. Our purpose is give a new proof of the following theorem, due to Fradelizi and Meyer [4].

Theorem 2. *Let f be non-negative and integrable. There exists $c \in \mathbb{R}^n$ such that c is a Santaló point for f with respect to any ρ . Moreover, if f is even then 0 is a Santaló point for f with respect to any weight.*

The even case goes back to Keith Ball in [2], this was the first example of a functional version of (1). Later on, Artstein, Klartag and Milman [1] proved that any integrable f admits a Santaló point with respect to the weight $t \mapsto e^{-t^2/2}$. Moreover in this case the barycenter of f suits (see [5]). Unfortunately this is not true in general; indeed, taking

$$\begin{aligned} f &= \mathbf{1}_{(-2,0)} + 4\mathbf{1}_{(0,1)} \\ g &= \mathbf{1}_{(-0.5,0]} + \frac{1}{4}\mathbf{1}_{(0,1)} \\ \rho &= \mathbf{1}_{[0,1]}, \end{aligned}$$

it is easy to check that f has its barycenter at 0, and that $f(s)g(t) \leq \rho(\sqrt{st})^2$ as soon as $st \geq 0$. However

$$\int_{\mathbb{R}} f(s) ds \int_{\mathbb{R}} g(t) dt = \frac{9}{2} > 4 = \left(\int_{\mathbb{R}} \rho(|r|) dr \right)^2.$$

To prove the existence of a Santaló point, the authors of [4] use a fixed point theorem and the usual Santaló inequality (for convex bodies). Our proof is direct, in the sense that it does not use the Blaschke Santaló inequality; it is based on a special form of the Prékopa-Leindler inequality and on a partition theorem due to Yao and Yao [8].

Lastly, the Blaschke-Santaló inequality follows very easily from Theorem 2: we let the reader check that if c is a Santaló point for $\mathbf{1}_K$ with respect to the weight $\mathbf{1}_{[0,1]}$ then c is a Santaló point for K .

1 Yao-Yao partitions

In the sequel we consider real affine spaces of finite dimension. If E is such a space we denote by \vec{E} the associated vector space. We say that \mathcal{P} is a partition of E if $\cup \mathcal{P} = E$ and if the interiors of two distinct elements of \mathcal{P} do not intersect. For instance, with this definition, the set $\{(-\infty, a], [a, +\infty)\}$ is a partition of \mathbb{R} . We define by induction on the dimension a class of partitions of an n -dimensional affine space.

Definition 3. If $E = \{c\}$ is an affine space of dimension 0, the only possible partition $\mathcal{P} = \{c\}$ is a Yao-Yao partition of E , and its center is defined to be c .

Let E be an affine space of dimension $n \geq 1$. A set \mathcal{P} is said to be a Yao-Yao partition of E if there exists an affine hyperplane F of E , a vector $v \in \vec{E} \setminus \vec{F}$ and two Yao-Yao partitions \mathcal{P}_+ and \mathcal{P}_- of F having the same center c such that

$$\mathcal{P} = \{A + \mathbb{R}_-v \mid A \in \mathcal{P}_-\} \cup \{A + \mathbb{R}_+v \mid A \in \mathcal{P}_+\},$$

The center of \mathcal{P} is then x .

If A is a subset of \vec{E} we denote by $\text{pos}(A)$ the positive hull of A , that is to say the smallest convex cone containing A .

A Yao-Yao partition \mathcal{P} of an n -dimensional space E has 2^n elements and for each A in \mathcal{P} there exists a basis v_1, \dots, v_n of \vec{E} such that

$$A = c + \text{pos}(v_1, \dots, v_n), \tag{4}$$

where c is the center of \mathcal{P} . Indeed, assume that \mathcal{P} is defined by F, v, \mathcal{P}_+ and \mathcal{P}_- (see Definition 3). Let $A \in \mathcal{P}_+$ and assume inductively that there is a basis v_1, \dots, v_{n-1} of \vec{F} such that $A = c + \text{pos}(v_1, \dots, v_{n-1})$. Then $A + \mathbb{R}_+v = c + \text{pos}(v, v_1, \dots, v_{n-1})$.

A fundamental property of this class of partitions is the following

Proposition 4. *Let \mathcal{P} be a Yao-Yao partition of E and c its center. Let ℓ be an affine form on E such that $\ell(c) = 0$. Then there exists $A \in \mathcal{P}$ such that $\ell(x) \geq 0$ for all $x \in A$. Moreover there is at most one element A of \mathcal{P} such that $\ell(x) > 0$ for all $x \in A \setminus \{c\}$.*

Proof. By induction on the dimension n of E . When $n = 0$ it is obvious, we assume that $n \geq 1$ and that the result holds for all affine spaces of dimension

$n - 1$. Let ℓ be an affine form on E such that $\ell(c) = 0$. We introduce $F, v, \mathcal{P}_+, \mathcal{P}_-$ given by Definition 3. By the induction assumption, there exists $A_+ \in \mathcal{P}_+$ and $A_- \in \mathcal{P}_-$ such that

$$\forall y \in A_+ \cup A_- \quad \ell(y) \geq 0.$$

If $\ell(c + v) \geq 0$ then $\ell(x + tv) \geq 0$ for all $x \in A_+$ and $t \in \mathbb{R}_+$, thus $\ell(x) \geq 0$ for all $x \in A_+ + \mathbb{R}_+v$. If on the contrary $\ell(c + v) \leq 0$ then $\ell(x) \geq 0$ for all $x \in A_- + \mathbb{R}_-v$, which proves the first part of the proposition. The proof of the ‘moreover’ part is similar. \square

The latter proposition yields the following corollary, which deals with dual cones: if C is cone of \mathbb{R}^n the dual cone of C is by definition

$$C^* = \{y \in \mathbb{R}^n \mid \forall x \in C, x \cdot y \geq 0\}.$$

Corollary 5. *Let \mathcal{P} be a Yao-Yao partition of \mathbb{R}^n centered at 0. Then*

$$\mathcal{P}^* := \{A^* \mid A \in \mathcal{P}\}$$

is also a partition of \mathbb{R}^n .

Actually the dual partition is also a Yao-Yao partition centered at 0 but we will not use this fact.

Proof. Let $x \in \mathbb{R}^n$ and $\ell : y \in \mathbb{R}^n \mapsto x \cdot y$. By the previous proposition there exists $A \in \mathcal{P}$ such that $\ell(y) \geq 0$ for all $y \in A$. Then $x \in A^*$. Thus $\cup \mathcal{P}^* = \mathbb{R}^n$. Moreover if x belongs to the interior of A^* , then for all $y \in A \setminus \{0\}$ we have $\ell(y) > 0$. Again by the proposition above there is at most one such A . Thus the interiors of two distinct elements of \mathcal{P}^* do not intersect. \square

We now let $\mathcal{M}(E)$ be the set of Borel measure μ on E which are finite and which satisfy $\mu(F) = 0$ for any affine hyperplane F .

Definition 6. Let $\mu \in \mathcal{M}(E)$, a Yao-Yao equipartition \mathcal{P} for μ is a Yao-Yao partition of E satisfying

$$\forall A \in \mathcal{P}, \quad \mu(A) = 2^{-n} \mu(E). \tag{5}$$

We say that $c \in E$ is a Yao-Yao center of μ if c is the center of a Yao-Yao equipartition for μ .

Here is the main result concerning those partitions.

Theorem 7. *Let $\mu \in \mathcal{M}(\mathbb{R}^n)$, there exists a Yao-Yao equipartition for μ . Moreover, if μ is even then 0 is a Yao-Yao center for μ .*

It is due to Yao and Yao [8]. They have some extra hypothesis on the measure and their paper is very sketchy, so we refer to [6] for a proof of this very statement.

2 Proof of the Fradelizi-Meyer inequality

In this section, all integrals are taken with respect to the Lebesgue measure. Let us recall the Prékopa-Leindler inequality, which is a functional form of the famous Brunn-Minkowski inequality, see for instance [3] for a proof and selected applications. If $\varphi_1, \varphi_2, \varphi_3$ are non-negative and integrable functions on \mathbb{R}^n satisfying $\varphi_1(x)^\lambda \varphi_2(y)^{1-\lambda} \leq \varphi_3(\lambda x + (1-\lambda)y)$ for all x, y in \mathbb{R}^n and for some fixed $\lambda \in (0, 1)$, then

$$\left(\int_{\mathbb{R}^n} \varphi_1 \right)^\lambda \left(\int_{\mathbb{R}^n} \varphi_2 \right)^{1-\lambda} \leq \int_{\mathbb{R}^n} \varphi_3.$$

The following lemma is a useful (see [4, 2]) logarithmic version of Prékopa-Leindler. We recall the proof for completeness.

Lemma 8. *Let f_1, f_2, f_3 be non-negative Borel functions on \mathbb{R}_+^n satisfying*

$$f_1(x)f_2(y) \leq \left(f(\sqrt{x_1y_1}, \dots, \sqrt{x_ny_n}) \right)^2$$

for all x, y in \mathbb{R}_+^n . Then

$$\int_{\mathbb{R}_+^n} f_1 \int_{\mathbb{R}_+^n} f_2 \leq \left(\int_{\mathbb{R}_+^n} f_3 \right)^2. \quad (6)$$

Proof. For $i = 1, 2, 3$ we let

$$g_i(x) = f_i(e^{x_1}, \dots, e^{x_n})e^{x_1 + \dots + x_n}.$$

Then by change of variable we have

$$\int_{\mathbb{R}^n} g_i = \int_{\mathbb{R}_+^n} f_i.$$

On the other hand the hypothesis on f_1, f_2, f_3 yields

$$g_1(x)g_2(y) \leq g_3\left(\frac{x+y}{2}\right),$$

for all x, y in \mathbb{R}^n . Then by Prékopa-Leindler

$$\int_{\mathbb{R}^n} g_1 \int_{\mathbb{R}^n} g_2 \leq \left(\int_{\mathbb{R}^n} g_3 \right)^2. \quad \square$$

Theorem 9. *Let f be a non-negative Borel integrable function on \mathbb{R}^n , and let c be a Yao-Yao center for the measure with density f . Then c is a Santaló point for f with respect to any weight.*

Combining this result with Theorem 7 we obtain a complete proof of the Fradelizi-Meyer inequality.

Proof. It is enough to prove that if 0 is a Yao-Yao center for f then 0 is a Santaló point. Indeed, if c is a center for f then 0 is a center for

$$f_c : x \mapsto f(c + x).$$

And if 0 is a Santaló point for f_c then c is a Santaló point for f .

Let \mathcal{P} be a Yao-Yao equipartition for f with center 0. Let g and ρ be such that (2) holds (with $c = 0$). Let $A \in \mathcal{P}$, by (4), there exists an operator T on \mathbb{R}^n with determinant 1 such that $A = T(\mathbb{R}_+^n)$. Let $S = (T^{-1})^*$, then $S(\mathbb{R}_+^n) = A^*$. Let $f_1 = f \circ T$, $f_2 = g \circ S$ and $f_3(x) = \rho(|x|)$. Since for all x, y we have $T(x) \cdot S(y) = x \cdot y$, we get from (2)

$$f_1(x)f_2(y) \leq \rho(\sqrt{x \cdot y})^2 = f_3(\sqrt{x_1y_1}, \dots, \sqrt{x_ny_n})^2,$$

for all x, y in \mathbb{R}_+^n . Applying the previous lemma we get (6). By change of variable it yields

$$\int_A f \int_{A^*} g \leq \left(\int_{\mathbb{R}_+^n} \rho(|x|) dx \right)^2.$$

Therefore

$$\sum_{A \in \mathcal{P}} \int_A f \int_{A^*} g \leq 2^n \left(\int_{\mathbb{R}_+^n} \rho(|x|) dx \right)^2. \quad (7)$$

Since \mathcal{P} is an equipartition for f we have for all $A \in \mathcal{P}$

$$\int_A f = 2^{-n} \int_{\mathbb{R}^n} f.$$

By Corollary 5, the set $\{A^*, A \in \mathcal{P}\}$ is a partition of \mathbb{R}^n , thus

$$\sum_{A \in \mathcal{P}} \int_{A^*} g = \int_{\mathbb{R}^n} g.$$

Inequality (7) becomes

$$\int_{\mathbb{R}^n} f \int_{\mathbb{R}^n} g \leq 4^n \left(\int_{\mathbb{R}_+^n} \rho(|x|) dx \right)^2,$$

and of course the latter is equal to $\left(\int_{\mathbb{R}^n} \rho(|x|) dx \right)^2$. □

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