

WEAK AND STRONG MOMENTS OF RANDOM VECTORS

RAFAL LATAŁA

*Institute of Mathematics, University of Warsaw
Banacha 2, 02-097 Warszawa, Poland
Institute of Mathematics, Polish Academy of Sciences
Śniadeckich 8, 00-956 Warszawa, Poland
E-mail: rlatala@mimuw.edu.pl*

Abstract. We discuss a conjecture about comparability of weak and strong moments of log-concave random vectors and show the conjectured inequality for unconditional vectors in normed spaces with a bounded cotype constant.

1. Introduction. Let X be a random vector with values in some normed space $(F, \|\cdot\|)$. The question we will discuss is how to estimate $\|X\|_p = (\mathbb{E}\|X\|^p)^{1/p}$ for $p \geq 1$. Obviously $\|X\|_p \geq \|X\|_1 = \mathbb{E}\|X\|$ and for any continuous linear functional φ on F with $\|\varphi\|_* \leq 1$ we have $\|X\|_p \geq (\mathbb{E}|\varphi(X)|^p)^{1/p}$. It turns out that in some situations one may reverse these obvious estimates and show that for an absolute constant C and any $p \geq 1$,

$$(\mathbb{E}\|X\|^p)^{1/p} \leq C \left(\mathbb{E}\|X\| + \sup_{\|\varphi\|_* \leq 1} (\mathbb{E}|\varphi(X)|^p)^{1/p} \right).$$

This is for example the case when X has Gaussian or product exponential distribution. In this note we will concentrate on the more general case of log-concave vectors.

A measure μ on \mathbb{R}^n is called logarithmically concave (log-concave in short) if for any compact nonempty sets $A, B \subset \mathbb{R}^n$ and $\lambda \in (0, 1)$,

$$\mu(\lambda A + (1 - \lambda)B) \geq \mu(A)^\lambda \mu(B)^{1-\lambda}.$$

By the result of Borell [3] a measure μ on \mathbb{R}^n with full dimensional support is log-concave if and only if it is absolutely continuous with respect to the Lebesgue measure and has a density of the form e^{-f} , where $f: \mathbb{R}^n \rightarrow (-\infty, \infty]$ is a convex function. Log-concave measures are frequently studied in convex geometry, since by the Brunn-Minkowski inequality

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uniform distributions on convex bodies as well as their lower dimensional marginals are log-concave. In fact the class of log-concave measures on \mathbb{R}^n is the smallest class of probability measures closed under linear transformation and weak limits that contains uniform distributions on convex bodies. Vectors with logarithmically concave distributions are called log-concave.

In the sequel we discuss the following conjecture posed in a stronger form in [5] about the comparison of strong and weak moment for log-concave vectors.

CONJECTURE 1.1. *For any n dimensional log-concave random vector and any norm $\|\cdot\|$ on \mathbb{R}^n we have for $1 \leq p < \infty$,*

$$(\mathbb{E}\|X\|^p)^{1/p} \leq C_1 \mathbb{E}\|X\| + C_2 \sup_{\|\varphi\|_* \leq 1} (\mathbb{E}|\varphi(X)|^p)^{1/p}, \quad (1)$$

where C_1 and C_2 are absolute constants.

In Section 2 we gather known results about validity of (1) in special cases. Section 3 is devoted to the unconditional vectors. In particular we show that Conjecture 1.1 is satisfied under additional assumption of unconditionality of X and bounded cotype constant of the underlying normed space.

Notation. Let (ε_i) be a Bernoulli sequence, i.e. a sequence of independent symmetric variables taking values ± 1 . We assume that (ε_i) are independent of other random variables.

By (\mathcal{E}_i) we denote a sequence of independent symmetric exponential random variables with variance 1 (i.e. the density $2^{-1/2} \exp(-\sqrt{2}|x|)$). We set $\mathcal{E} = \mathcal{E}^{(n)} = (\mathcal{E}_1, \dots, \mathcal{E}_n)$ for an n -dimensional random vector with product exponential distribution and identity covariance matrix.

By $\langle \cdot, \cdot \rangle$ we denote the standard scalar product on \mathbb{R}^n and by (e_i) the standard basis of \mathbb{R}^n . We set B_p^n for a unit ball in ℓ_p^n , i.e. $B_p^n = \{x \in \mathbb{R}^n : \|x\|_p \leq 1\}$. For a random variable Y and $p > 0$ we write $\|Y\|_p = (\mathbb{E}|Y|^p)^{1/p}$.

We write C (resp. $C(\alpha)$) to denote universal constants (resp. constants depending only on parameter α). Value of a constant C may differ at each occurrence.

2. Known results. Since any norm on \mathbb{R}^n may be approximated by a supremum of exponential number of functionals we get

PROPOSITION 2.1 (see [5, Proposition 3.20]). *For any n -dimensional random vector X inequality (1) holds for $p \geq n$ with $C_1 = 0$ and $C_2 = 10$.*

It is also easy to reduce Conjecture 1.1 to the case of symmetric vectors.

PROPOSITION 2.2. *Suppose that (1) holds for all symmetric n -dimensional log-concave vectors X . Then it is also satisfied with constants $4C_1 + 1$ and $4C_2$ by all log-concave vectors X .*

Proof. Assume first that X has a log-concave distribution and $\mathbb{E}X = 0$. Let X' be an

independent copy of X , then $X - X'$ is symmetric and log-concave. Moreover for $p \geq 1$,

$$\begin{aligned} (\mathbb{E}\|X\|^p)^{1/p} &= (\mathbb{E}\|X - \mathbb{E}X'\|^p)^{1/p} \leq (\mathbb{E}\|X - X'\|^p)^{1/p}, \\ \mathbb{E}\|X - X'\| &\leq \mathbb{E}\|X\| + \mathbb{E}\|X'\| = 2\mathbb{E}\|X\| \end{aligned}$$

and for any functional φ ,

$$(\mathbb{E}|\varphi(X - X')|^p)^{1/p} \leq (\mathbb{E}|\varphi(X)|^p)^{1/p} + (\mathbb{E}|\varphi(X')|^p)^{1/p} = 2(\mathbb{E}|\varphi(X)|^p)^{1/p}$$

Hence (1) holds for X with constant $2C_1$ and $2C_2$.

If X is arbitrary log-concave then $X - \mathbb{E}X$ is log-concave with mean zero. We have for any $p \geq 1$,

$$(\mathbb{E}\|X\|^p)^{1/p} \leq (\mathbb{E}\|X - \mathbb{E}X\|^p)^{1/p} + \mathbb{E}\|X\|, \quad \mathbb{E}\|X - \mathbb{E}X\| \leq 2\mathbb{E}\|X\|$$

and for any functional φ ,

$$(\mathbb{E}|\varphi(X - \mathbb{E}X)|^p)^{1/p} \leq (\mathbb{E}|\varphi(X)|^p)^{1/p} + |\varphi(\mathbb{E}X)| \leq 2(\mathbb{E}|\varphi(X)|^p)^{1/p}.$$

■

REMARK. Estimating $\|X\|_p$ is strictly connected with bounding tails of $\|X\|$. Indeed by Chebyshev's inequality we have

$$\mathbb{P}(\|X\| \geq e\|X\|_p) \leq e^{-p}$$

and by the Paley-Zygmund inequality and the fact that $\|X\|_{2p} \leq C\|X\|_p$ for $p \geq 1$ we get

$$\mathbb{P}\left(\|X\| \geq \frac{1}{C}\|X\|_p\right) \geq \min\left\{\frac{1}{C}, e^{-p}\right\}.$$

Gaussian concentration inequality easily implies (1) for Gaussian vectors X (see for example Chapter 3 of [8]). For Rademacher sums comparability of weak and strong moments was established by Dilworth and Montgomery-Smith [4]. More general statement was shown in [6].

THEOREM 2.3. *Suppose that $X = \sum_i v_i \xi_i$, where $v_i \in F$ and ξ_i are independent symmetric r.v.'s with logarithmically concave tails. Then for any $p \geq 1$ inequality (1) holds with absolute constants C_1 and C_2 .*

This immediately implies

COROLLARY 2.4. *Conjecture 1.1 holds under additional assumption that coordinates of X are independent.*

Proof. We have $X = \sum_{i=1}^n e_i X_i$ with X_i independent log-concave real random variables. It is enough to notice that variables X_i have log-concave tails and in the symmetric case apply Theorem 2.3. General independent case may be reduce to the symmetric one as in the proof of Proposition 2.2. ■

The crucial tool in the proof of Theorem 2.3 is the Talagrand two-level concentration inequality for the product exponential distribution [12]:

$$\nu^n(A) \geq \frac{1}{2} \quad \Rightarrow \quad 1 - \nu^n(A + \sqrt{t}B_2^n + tB_1^n) \leq e^{-t/C}, \quad t > 0,$$

where ν is the symmetric exponential distribution, i.e. $d\nu(x) = \frac{1}{2} \exp(-|x|)dx$.

In [5] more general concentration inequalities were investigated. For a probability measure μ on \mathbb{R}^n define

$$\Lambda_\mu(y) = \log \int e^{\langle y, z \rangle} d\mu(z), \quad \Lambda_\mu^*(x) = \sup_y (\langle y, x \rangle - \Lambda_\mu(y))$$

and

$$B_\mu(t) = \{x \in \mathbb{R}^n : \Lambda_\mu(x) \leq t\}.$$

One may show that $B_{\nu^n}(t) \sim \sqrt{t}B_2^n + tB_1^n$. Argument presented in [5, Section 3.3] gives

PROPOSITION 2.5. *Suppose that for some $\alpha \geq 1$ and $\beta > 0$ and any convex symmetric compact set $K \subset \mathbb{R}^n$ we have*

$$\mu(K) \geq \frac{1}{2} \quad \Rightarrow \quad 1 - \mu(\alpha K + B_\mu(t)) \leq e^{-t/\beta}, \quad \text{for all } t > 0. \quad (2)$$

Then inequality (1) holds with $C_1 = \alpha$ and $C_2 = C\beta$.

In [5] it was shown that concentration inequality (2) holds with $\alpha = 1$ for symmetric product log-concave measures and for uniform distributions on B_r^n balls. This gives

COROLLARY 2.6. *Inequality (1) holds with $C_1 = 1$ and universal C_2 for uniform distributions on B_r^n balls $1 \leq r \leq \infty$.*

Modification of Paouris' proof [11] of large deviation inequality for ℓ_2 norm of isotropic log-concave vectors shows that weak and strong moments are comparable in the Euclidean case (see [1] for details):

THEOREM 2.7. *If X is a log-concave n -dimensional random vector then for any Euclidean norm $\|\cdot\|$ on \mathbb{R}^n we have*

$$(\mathbb{E}\|X\|^p)^{1/p} \leq C \left(\mathbb{E}\|X\| + \sup_{\|\varphi\|_* \leq 1} (\mathbb{E}|\varphi(X)|^p)^{1/p} \right).$$

3. Unconditional case. We say that a random vector $X = (X_1, \dots, X_n)$ has *unconditional distribution* if the distribution of $(\eta_1 X_1, \dots, \eta_n X_n)$ is the same as X for any choice of signs η_1, \dots, η_n . Random vector X is called *isotropic* if it has identity covariance matrix, i.e. $\text{Cov}(X_i, X_j) = \delta_{i,j}$.

THEOREM 3.1. *Suppose that X is an n -dimensional isotropic, unconditional, log-concave vector. Then for any norm $\|\cdot\|$ on \mathbb{R}^n and $p \geq 1$,*

$$(\mathbb{E}\|X\|^p)^{1/p} \leq C \left(\mathbb{E}\|\mathcal{E}\| + \sup_{\|\varphi\|_* \leq 1} (\mathbb{E}|\varphi(X)|^p)^{1/p} \right). \quad (3)$$

Proof. Let $T = \{t \in \mathbb{R}^n : \|t\|_* \leq 1\}$ be the unit ball in the space $(\mathbb{R}^n, \|\cdot\|_*)$ dual to $(\mathbb{R}^n, \|\cdot\|)$. Then $\|x\| = \sup_{t \in T} \langle t, x \rangle$. By the result of Talagrand [13] (see also [14]) there exist subsets $T_n \subset T$ and functions $\pi_n : T \rightarrow T_n$, $n = 0, 1, \dots$ such that $\pi_n(t) \rightarrow t$ for all $t \in T$, $\#T_0 = 1$, $\#T_n \leq 2^{2^n}$ and

$$\sum_{n=0}^{\infty} \|\langle \pi_{n+1}(t) - \pi_n(t), \mathcal{E} \rangle\|_{2^n} \leq C \mathbb{E} \sup_{t \in T} \langle t, \mathcal{E} \rangle = C \mathbb{E}\|\mathcal{E}\|. \quad (4)$$

Let us fix $p \geq 1$ and choose $n_0 \geq 1$ such that $2^{n_0-1} < 2p \leq 2^{n_0}$. We have

$$\|X\| = \sup_{t \in T} \langle t, X \rangle \leq \sup_{t \in T} |\langle \pi_{n_0}(t), X \rangle| + \sup_{t \in T} \sum_{n=n_0}^{\infty} |\langle \pi_{n+1}(t) - \pi_n(t), X \rangle|. \quad (5)$$

We get

$$\begin{aligned} \left(\mathbb{E} \sup_{t \in T} |\langle \pi_{n_0}(t), X \rangle|^p \right)^{1/p} &\leq \left(\mathbb{E} \sum_{s \in T_{n_0}} | \langle s, X \rangle|^p \right)^{1/p} \leq (\#T_{n_0})^{1/p} \sup_{s \in T_{n_0}} (\mathbb{E} | \langle s, X \rangle|^p)^{1/p} \\ &\leq 16 \sup_{t \in T} (\mathbb{E} | \langle t, X \rangle|^p)^{1/p} = 16 \sup_{\|\varphi\|_* \leq 1} (\mathbb{E} | \varphi(X) |^p)^{1/p}. \end{aligned} \quad (6)$$

To estimate the last term in (5) notice that for $u \geq 16$ we have by Chebyshev's inequality

$$\begin{aligned} \mathbb{P} \left(\sup_{t \in T} \sum_{n=n_0}^{\infty} |\langle \pi_{n+1}(t) - \pi_n(t), X \rangle| \geq u \sup_{t \in T} \sum_{n=n_0}^{\infty} \|\langle \pi_{n+1}(t) - \pi_n(t), X \rangle\|_{2^n} \right) \\ \leq \mathbb{P} \left(\exists_{n \geq n_0} \exists_{t \in T} |\langle \pi_{n+1}(t) - \pi_n(t), X \rangle| \geq u \|\langle \pi_{n+1}(t) - \pi_n(t), X \rangle\|_{2^n} \right) \\ \leq \sum_{n=n_0}^{\infty} \sum_{s \in T_{n+1}} \sum_{s' \in T_n} \mathbb{P}(| \langle s - s', X \rangle | \geq u \| \langle s - s', X \rangle \|_{2^n}) \leq \sum_{n=n_0}^{\infty} \#T_{n+1} \#T_n u^{-2^n} \\ \leq \sum_{n=n_0}^{\infty} \left(\frac{8}{u} \right)^{2^n} \leq 2 \left(\frac{8}{u} \right)^{2^{n_0}} \leq 2 \left(\frac{8}{u} \right)^{2p}. \end{aligned}$$

Integrating by parts this gives

$$\begin{aligned} \left(\mathbb{E} \left(\sup_{t \in T} \sum_{n=n_0}^{\infty} |\langle \pi_{n+1}(t) - \pi_n(t), X \rangle| \right)^p \right)^{1/p} \\ \leq \sup_{t \in T} \sum_{n=n_0}^{\infty} \|\langle \pi_{n+1}(t) - \pi_n(t), X \rangle\|_{2^n} \left(16 + \left(2p \int_0^{\infty} u^{p-1} \left(\frac{8}{u+16} \right)^{2p} \right)^{1/p} \right) \\ \leq 32 \sup_{t \in T} \sum_{n=n_0}^{\infty} \|\langle \pi_{n+1}(t) - \pi_n(t), X \rangle\|_{2^n}. \end{aligned} \quad (7)$$

The result of Bobkov and Nazarov [2] gives

$$\|\langle t, X \rangle\|_r \leq C \|\langle t, \mathcal{E} \rangle\|_r \quad \text{for any } t \in \mathbb{R}^n \text{ and } r \geq 1. \quad (8)$$

Thus the statement follows by (4)-(7). ■

REMARK. The only property of the vector X that was used in the above proof was estimate (8). Thus inequality (3) holds for all n -dimensional random vectors satisfying (8).

REMARK. Estimate (8) gives $(\mathbb{E} |\varphi(X)|^p)^{1/p} \leq C (\mathbb{E} |\varphi(\mathcal{E})|^p)^{1/p}$ for any functional φ , therefore Theorem 3.1 is stronger than the estimate from [7]:

$$(\mathbb{E} \|X\|^p)^{1/p} \leq C \mathbb{E} \|\mathcal{E}\|^p \sim C \left(\mathbb{E} \|\mathcal{E}\| + \sup_{\|\varphi\|_* \leq 1} (\mathbb{E} |\varphi(\mathcal{E})|^p)^{1/p} \right).$$

In some situation one may show that $\mathbb{E}\|\mathcal{E}\| \leq C\mathbb{E}\|X\|$. This is the case of spaces with bounded cotype constant.

COROLLARY 3.2. *Suppose that $2 \leq q < \infty$, $F = (\mathbb{R}^n, \|\cdot\|)$ is a finite dimensional space with a q -cotype constant bounded by $\beta < \infty$. Then for any n -dimensional unconditional, log-concave vector X and $p \geq 1$,*

$$(\mathbb{E}\|X\|^p)^{1/p} \leq C(q, \beta) \left(\mathbb{E}\|X\| + \sup_{\|\varphi\|_* \leq 1} (\mathbb{E}|\varphi(X)|^p)^{1/p} \right),$$

where $C(q, \beta)$ is a constant that depends only on q and β .

Proof. Applying diagonal transformation (and appropriately changing the norm) we may assume that X is also isotropic.

By the result of Maurey and Pisier [9] (see also Appendix II in [10]) one has

$$\mathbb{E}\|\mathcal{E}\| = \mathbb{E} \left\| \sum_{i=1}^n e_i \mathcal{E}_i \right\| \leq C_1(q, \beta) \mathbb{E} \left\| \sum_{i=1}^n e_i \varepsilon_i \right\|.$$

By the unconditionality of X and Jensen's inequality we get

$$\mathbb{E}\|X\| = \mathbb{E} \left\| \sum_{i=1}^n e_i \varepsilon_i |X_i| \right\| \geq \mathbb{E} \left\| \sum_{i=1}^n e_i \varepsilon_i \mathbb{E}|X_i| \right\|.$$

We have $\mathbb{E}|X_i| \geq \frac{1}{C}(\mathbb{E}|X_i|^2)^{1/2} = \frac{1}{C}$, therefore

$$\mathbb{E}\|\mathcal{E}\| \leq CC_1(q, \beta)\mathbb{E}\|X\|$$

and the statement follows by Theorem 3.1. ■

For general norm on \mathbb{R}^n one has

$$\mathbb{E}\|\mathcal{E}\| = \mathbb{E} \left\| \sum_{i=1}^n e_i \varepsilon_i |\mathcal{E}_i| \right\| \leq \mathbb{E} \sup_i |\mathcal{E}_i| \mathbb{E} \left\| \sum_{i=1}^n e_i \varepsilon_i \right\| \leq C \log n \mathbb{E} \left\| \sum_{i=1}^n e_i \varepsilon_i \right\|.$$

This together with the similar argument as in the proof of Corollary 3.2 gives the following.

COROLLARY 3.3. *For any n -dimensional unconditional, log-concave vector X , any norm $\|\cdot\|$ on \mathbb{R}^n and $p \geq 1$ one has*

$$(\mathbb{E}\|X\|^p)^{1/p} \leq C \left(\log n \mathbb{E}\|X\| + \sup_{\|\varphi\|_* \leq 1} (\mathbb{E}|\varphi(X)|^p)^{1/p} \right).$$

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