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Bounded linear functionals on the n-normed space of p-summable sequences

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Abstract
Let $(X, \|\cdot, \cdots, \cdot\|)$ be a real n-normed space, as introduced by S. Gähler in 1969. We shall be interested in bounded linear functionals on X, using the n-norm as our main tool. We study the duality properties and show that the space X' of bounded linear functionals on X also forms an n-normed space. We shall present more results on bounded multilinear n-functionals on the space of p-summable sequences being equipped with an n-norm. Open problems are also posed.

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1 Introduction

Let n be a nonnegative integer and X be a real vector space of dimension $d \geq n$. A real-valued function $\|\cdot, \dots, \cdot\|$ on X^n satisfying the following four properties:

N.1 $\|x_1, \dots, x_n\| = 0$ if and only if $x_1, \dots, x_n$ are linearly dependent,

N.2 $\|x_1, \dots, x_n\|$ is invariant under permutation,

N.3 $\|\alpha x_1, \dots, x_n\| = |\alpha| \, \|x_1, \dots, x_n\|$ for any $\alpha \in \mathbb{R}$,

N.4 $\|x_1 + x_1', x_2, \dots, x_n\| \leq \|x_1, x_2, \dots, x_n\| + \|x_1', x_2, \dots, x_n\|$,

is called an *n-norm* on X, and the pair $(X, \|\cdot, \dots, \cdot\|)$ is called an n-normed space.

In an n-normed space $(X, \|\cdot, \dots, \cdot\|)$, one may observe that $\|x_1, \dots, x_n\| \geq 0$ and

$$\|x_1 + \alpha_2 x_2 + \cdots + \alpha_n x_n, x_2, \dots, x_n\| = \|x_1, x_2, \dots, x_n\| \tag{1.1}$$

for every $x_1, \dots, x_n \in X$ and $\alpha_2, \dots, \alpha_n \in \mathbb{R}$.

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If $(X, \|\cdot\|)$ is a normed space and X' is its dual (consisting of bounded linear functionals on X), the following function defines an n-norm on X:

$$\|x_1, \dots, x_n\|^G := \sup_{f_i \in X', \ \|f_i\| \le 1} \begin{vmatrix} f_1(x_1) & \cdots & f_n(x_1) \\ \vdots & \ddots & \vdots \\ f_1(x_n) & \cdots & f_n(x_n) \end{vmatrix}. \tag{1.2}$$

Note that the determinant on the right hand side may be negative for certain f_i's, but in such a case we may replace one of the f_i's by its negative, so that the supremum of these determinants is always nonnegative.

For another example, if $(X, \langle \cdot, \cdot \rangle)$ is an inner product space, we can define the standard n-norm on X by

$$\|x_1, \dots, x_n\|^S := \begin{vmatrix} \langle x_1, x_1 \rangle & \cdots & \langle x_1, x_n \rangle) \\ \vdots & \ddots & \vdots \\ \langle x_n, x_1 \rangle & \cdots & \langle x_n, x_n \rangle \end{vmatrix}^{1/2}. \tag{1.3}$$

The determinant above is known as Gram's determinant, whose value is always nonnegative. Geometrically, the value of $\|x_1, \dots, x_n\|^S$ represents the volume of the n-dimensional parallelepiped spanned by $x_1, \dots, x_n$ (see [5]).

The concept of n-normed spaces was initially introduced by Gähler [1, 2, 3, 4] in the 1960's. Recent results and related topics may be found in [8, 9, 10, 7, 11].

In this paper, we shall be interested in studying bounded linear functionals on X, using the n-norm as our main tool. We prove an analog of the Riesz-Fréchet Theorem and show that the dual space X', consisting of all bounded linear functionals on X, also forms an n-normed space. We shall present more results when X is the space of p-summable sequences being equipped with an n-norm. In addition, some open problems will be posed.

2 Bounded Linear Functionals

Let $(X, \|\cdot, \dots, \cdot\|)$ be a real n-normed space and $f : X \to \mathbb{R}$ be a linear functional on X. We may define bounded linear functionals on X by using the n-norm in several ways as follows.

2.1 Bounded linear functionals (of 1st index)

Fix a linearly independent set $Y := \{y_1, \dots, y_n\}$ in X. We say that f is *bounded with respect to* Y if and only if there exists $K > 0$ such that

$$|f(x)| \le K \sum \|x, y_{i_2}, \dots, y_{i_n}\| \tag{2.1}$$

for all $x \in X$, where the sum is taken over $\{i_2, \dots, i_n\} \subset \{1, \dots, n\}$ with $i_2 < \cdots < i_n$. [One might ask why we do not just take a linearly independent set $\{y_2, \dots, y_n\}$ in X and put $|f(x)| \le K \|x, y_2, \dots, y_n\|$ for all $x \in X$. The drawback with this is that for a nonzero vector x in the linear span of $\{y_2, \dots, y_n\}$, we have $\|x, y_2, \dots, y_n\| = 0$ while $f(x) \ne 0$. This problem is overcome by taking a set of n linearly independent vectors and form the sum as in (2.1). Indeed, one might observe that the sum is equal to 0 if and only if $x = 0$.]

For simplicity, we shall say 'bounded' instead of 'bounded with respect to Y'. Clearly the set X'_1 of all linear functionals which are bounded on X forms a vector space. Now, for $f \in X'_1$, we define

$$\|f\|_1 := \inf\{K > 0 : (2.1) \text{ holds}\}. \tag{2.2}$$

It is easy to see that

$$\|f\|_1 = \sup\{|f(x)| \,:\, \sum\|x, y_{i_2}, \dots, y_{i_n}\| \le 1\}$$

Moreover, the formula (2.2) defines a norm on X_1'.

To give an example, we invoke the notion of n-inner product spaces [11]. Assume that X is of dimension $d \ge n+1$. A real-valued function $\langle \cdot, \cdot | \cdot, \dots, \cdot \rangle$ on X^{n+1} satisfying the following properties:

I.1 $\langle x_1, x_1 | x_2, \dots, x_n \rangle \ge 0$ and it is equal to 0 if and only if $x_1, \dots, x_n$ are linearly dependent,

I.2 $\langle x_{i_1}, x_{i_1} | x_{i_2}, \dots, x_{i_n} \rangle = \langle x_1, x_1 | x_2, \dots, x_n \rangle$ for any permutation $\{i_1, \dots, i_n\}$ of $\{1, \dots, n\}$,

I.3 $\langle x, y | x_2, \dots, x_n \rangle = \langle y, x | x_2, \dots, x_n \rangle$,

I.4 $\langle \alpha x, y | x_2, \dots, x_n \rangle = \alpha \langle x, y | x_2, \dots, x_n \rangle$ for any $\alpha \in \mathbb{R}$,

I.5 $\langle x + x', y | x_2, \dots, x_n \rangle = \langle x, y | x_2, \dots, x_n \rangle + \langle x', y | x_2, \dots, x_n \rangle$,

is called an *n-inner product* on X, and the pair $(X, \langle \cdot, \cdot | \cdot, \dots, \cdot \rangle)$ is called an *n-inner product space*.

Note that if $(X, \langle \cdot, \cdot | \cdot, \dots, \cdot \rangle)$ is an n-inner product space, then we can define an n-norm $\|\cdot, \dots, \cdot\|$ on X by

$$\|x_1, x_2, \dots, x_n\| := \langle x_1, x_1 | x_2, \dots, x_n \rangle^{1/2}.$$

Here we have the Cauchy-Schwarz inequality:

$$|\langle x, y | x_2, \dots, x_n \rangle| \le \|x, x_2, \dots, x_n\| \, \|y, x_2, \dots, x_n\|.$$

Now we give an example of bounded linear functionals on X. Let $(X, \langle \cdot, \cdot | \cdot, \dots, \cdot \rangle)$ be an n-inner product space, and $\|\cdot, \dots, \cdot\| := \langle \cdot, \cdot | \cdot, \dots, \cdot \rangle^{1/2}$ be the induced n-norm on X. With respect to the set $Y = \{y_1, \dots, y_n\}$, define $f : X \to \mathbb{R}$ by

$$f(x) := \sum \langle x, y_{i_1} | y_{i_2}, \dots, y_{i_n} \rangle, \tag{2.3}$$

where the sum is taken over $\{i_2, \dots, i_n\} \subset \{1, \dots, n\}$ with $i_2 < \dots < i_n$ and $i_1 \in \{1, \dots, n\} \setminus \{i_2, \dots, i_n\}$. Clearly f is linear. Furthermore, we have:

Fact 1. The linear functional f defined by (2.3) is bounded with $\|f\|_1 = \|y_1, \dots, y_n\|$.

Proof. We observe that for every $x \in X$, we have

$$\begin{aligned} |f(x)| &\le \sum |\langle x, y_{i_1} | y_{i_2}, \dots, y_{i_n} \rangle| \\ &\le \sum \|x, y_{i_2}, \dots, y_{i_n}\| \, \|y_{i_1}, y_{i_2}, \dots, y_{i_n}\| \\ &= \|y_1, \dots, y_n\| \sum \|x, y_{i_2}, \dots, y_{i_n}\| \end{aligned}$$

where the sum is taken over $\{i_2, \dots, i_n\} \subset \{1, \dots, n\}$ with $i_2 < \dots < i_n$. Thus f is bounded with $\|f\|_1 \le \|y_1, \dots, y_n\|$.

To show that $\|f\|_1 = \|y_1, \dots, y_n\|$, just take $x := \|y_1, \dots, y_n\|^{-1} y_1$. Then we see that $\sum \|x, y_{i_2}, \dots, y_{i_n}\| = 1$ and

$$\begin{aligned} |f(x)| &= \|y_1, \dots, y_n\|^{-1} f(y_1) \\ &= \|y_1, \dots, y_n\|^{-1} \sum \langle y_1, y_{i_1} | y_{i_2}, \dots, y_{i_n} \rangle \\ &= \|y_1, \dots, y_n\|^{-1} \langle y_1, y_1 | y_2, \dots, y_n \rangle \\ &= \|y_1, \dots, y_n\|^{-1} \|y_1, \dots, y_n\|^2 \\ &= \|y_1, \dots, y_n\|. \end{aligned}$$

[Note that when $i_1 \neq 1$ and $\{i_2, \ldots, i_n\} = \{1, \ldots, n\} \setminus \{i_1\}$, we have

$$|\langle y_1, y_{i_1} | y_{i_2}, \ldots, y_{i_n} \rangle| \leq \|y_1, y_{i_2}, \ldots, y_{i_n}\| \, \|y_{i_1}, y_{i_2}, \ldots, y_{i_n}\| = 0$$

because one of $y_{i_2}, \ldots, y_{i_n}$ must be equal to y_1.] □

2.2 Bounded linear functionals of p-th index

Fix a linearly independent set $Y := \{y_1, \ldots, y_n\}$ in X and $1 \leq p \leq \infty$. We say that f is *bounded of p-th index* (with respect to Y) if and only if there exists $K > 0$ such that

$$|f(x)| \leq K \left(\sum \|x, y_{i_2}, \ldots, y_{i_n}\|^p\right)^{1/p} \tag{2.4}$$

where the sum is taken over $\{i_2, \ldots, i_n\} \subset \{1, \ldots, n\}$ with $i_2 < \cdots < i_n$. [If $p = \infty$, then the sum is the maximum of all possible values of $\|x, y_{i_2}, \ldots, y_{i_n}\|$.]

As in the case where $p = 1$, the set X'_p of all linear functionals which are bounded of p-index on X forms a vector space. Now, for $f \in X'_p$, we define

$$\|f\|_p := \inf\{K > 0 \,:\, (2.4) \text{ holds}\}. \tag{2.5}$$

One then has

$$\|f\|_p = \sup\{|f(x)| \,:\, \sum \|x, y_{i_2}, \ldots, y_{i_n}\|^p \leq 1\}.$$

Moreover, the formula (2.5) defines a norm on X'_p.

Fact 2. The linear functional f defined by (2.3) is bounded of p-th index with $\|f\|_p = n^{1/p'} \|y_1, \ldots, y_n\|$, where p' is the dual exponent of p (that is, $\frac{1}{p} + \frac{1}{p'} = 1$).

Proof. For every $x \in X$, it follows from Hölder's inequality that

$$|f(x)| \leq \sum \|x, y_{i_2}, \ldots, y_{i_n}\| \, \|y_1, \ldots, y_n\| \leq n^{1/p'} \|y_1, \ldots, y_n\| \left(\sum \|x, y_{i_2}, \ldots, y_{i_n}\|^p\right)^{1/p},$$

whence $\|f\|_p \leq n^{1/p'} \|y_1, \ldots, y_n\|$.

To obtain the equality, take $x := n^{-1/p} \|y_1, \ldots, y_n\|^{-1}(y_1 + \cdots + y_n)$. Then, using (1.1), one may verify that $\sum \|x, y_{i_2}, \ldots, y_{i_n}\|^p = 1$. Moreover, we have

$$\begin{aligned} f(x) &= n^{-1/p} \|y_1, \ldots, y_n\|^{-1} \sum \langle y_1 + \cdots + y_n, y_{i_1} | y_{i_2}, \ldots, y_{i_n} \rangle \\ &= n^{-1/p} \|y_1, \ldots, y_n\|^{-1} \sum \langle y_{i_1}, y_{i_1} | y_{i_2}, \ldots, y_{i_n} \rangle \\ &= n^{-1/p} \|y_1, \ldots, y_n\|^{-1} \cdot n \, \|y_1, \ldots, y_n\|^2 \\ &= n^{1/p'} \|y_1, \ldots, y_n\|. \end{aligned}$$

This convinces us that $\|f\|_p = n^{1/p'} \|y_1, \ldots, y_n\|$. □

The following theorem tells us that X'_1 and X'_p are identical as a set.

Theorem 3. *Let f be a linear functional on X. If f is bounded of 1st index, then f is bounded of p-th index; and vice versa. In other words, $X'_1 = X'_p$.*

Proof. Suppose that f is bounded of p-index (with respect to $Y = \{y_1, \ldots, y_n\}$). If x satisfies $\sum \|x, y_{i_2}, \ldots, y_{i_n}\| \leq 1$, then each term of the sum is less than 1, i.e., $\|x, y_{i_2}, \ldots, y_{i_n}\| \leq 1$. Hence $\|x, y_{i_2}, \ldots, y_{i_n}\|^p \leq \|x, y_{i_2}, \ldots, y_{i_n}\|$, and so

$$\sum \|x, y_{i_2}, \ldots, y_{i_n}\|^p \leq \sum \|x, y_{i_2}, \ldots, y_{i_n}\| \leq 1.$$

Consequently, $|f(x)| \leq \|f\|_p$, and thus f is bounded of 1st index with $\|f\|_1 \leq \|f\|_p$.

Conversely, suppose that f is bounded of 1st index. If x satisfies $\sum \|x, y_{i_2}, \ldots, y_{i_n}\|^p \leq 1$, then $\sum \|x, y_{i_2}, \ldots, y_{i_n}\| \leq n^{1/p'}$, where p' is the dual exponent of p. Hence

$$\sum \| \tfrac{x}{n^{1/p'}}, y_{i_2}, \ldots, y_{i_n}\| \leq 1,$$

and so $\left|f\left(\frac{x}{n^{1/p'}}\right)\right| \leq \|f\|_1$ or $|f(x)| \leq n^{1/p'}\|f\|_1$. We therefore conclude that f is bounded of p-th index with $\|f\|_p \leq n^{1/p'}\|f\|_1$. □

Remark 4. Unless we need to specify the index explicitly, we may simply use the word 'bounded' instead of 'bounded of p-th index'. We also denote by X' the set of all bounded linear functionals on X and call it the *dual space* of X (with respect to Y). Theorem 3 states further that, on X', the norms $\|\cdot\|_p$ are all equivalent to $\|\cdot\|_1$, with

$$\|f\|_1 \leq \|f\|_p \leq n^{1/p'}\, \|f\|_1,$$

for every $f \in X'$.

2.3 Duality properties for $p = 2$

Let us now discuss another example of bounded linear functionals on the n-inner product space X, using the linearly independent set $Y = \{y_1, \ldots, y_n\}$. Let $y \neq y_i$ for $i = 1, \ldots, n$. Define $f_y : X \to \mathbb{R}$ by

$$f_y(x) := \sum \langle x, y | y_{i_2}, \ldots, y_{i_n}\rangle, \tag{2.6}$$

where the sum is taken over $\{i_2, \ldots, i_n\} \subset \{1, \ldots, n\}$ with $i_2 < \cdots < i_n$. Then f_y is linear. Moreover, we have:

Fact 5. The linear functional f_y defined by (2.6) is bounded of 2nd index with $\|f_y\|_2 = \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{1/2}$.

Proof. For every $x \in X$, it follows from Cauchy-Schwarz inequalities that

$$\begin{aligned} |f_y(x)| &\leq \sum |\langle x, y | y_{i_2}, \ldots, y_{i_n}\rangle| \\ &\leq \sum \|x, y_{i_2}, \ldots, y_{i_n}\|\, \|y, y_{i_2}, \ldots, y_{i_n}\| \\ &\leq \left(\sum \|x, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{1/2} \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{1/2}, \end{aligned}$$

whence $\|f_y\|_2 \leq \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{1/2}$.

Now, if we take $x := \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{-1/2} y$, we get

$$\begin{aligned} f_y(x) &= \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{-1/2} f_y(y) \\ &= \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{-1/2} \sum \langle y, y | y_{i_2}, \ldots, y_{i_n}\rangle \\ &= \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{-1/2} \sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2 \\ &= \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{1/2}. \end{aligned}$$

We must therefore have $\|f_y\|_2 = \left(\sum \|y, y_{i_2}, \ldots, y_{i_n}\|^2\right)^{1/2}$. □

It is desirable to have an analog of the Riesz-Fréchet Theorem for linear functionals which are bounded of 2nd index on an n-inner product space. For that, we import the following theorem from [9].

Theorem 6 ([9]). *Let $(X, \langle\cdot,\cdot|\cdot,\dots,\cdot\rangle)$ be an n-inner product space and $\|\cdot,\dots,\cdot\| = \langle\cdot,\cdot|\cdot,\dots,\cdot\rangle^{1/2}$ be the induced n-norm on X. With respect to the linearly independent set $Y = \{y_1,\dots,y_n\}$, the mapping $\langle\cdot,\cdot\rangle : X \times X \to \mathbb{R}$ given by*

$$\langle x, y\rangle := \sum \langle x, y|y_{i_2},\dots,y_{i_n}\rangle \tag{2.7}$$

defines an inner product on X, and its induced norm $\|\cdot\|_2 : X \to \mathbb{R}$ is given by

$$\|x\|_2 := \left(\sum \|x, y_{i_2},\dots,y_{i_n}\|^2\right)^{1/2}. \tag{2.8}$$

Corollary 7. *If $(X, \langle\cdot,\cdot|\cdot,\dots,\cdot\rangle)$ is complete with respect to the norm $\|\cdot\|_2$ in (2.8), then for every linear functional f which is bounded of 2nd index on X there exists a unique $y \in X$ such that*

$$f(x) = \langle x, y\rangle, \quad x \in X,$$

where $\langle\cdot,\cdot\rangle$ is the inner product in (2.7). Moreover, we have $\|y\|_2 = \|f\|_2$.

Theorem 8. *Let $(X, \|\cdot,\dots,\cdot\|)$ be an n-normed space, X' be the dual space of X (with respect to Y), and $\|\cdot\|_2$ be the derived norm on X given by*

$$\|x\|_2 := \left(\sum \|x, y_{i_2},\dots,y_{i_n}\|^2\right)^{1/2}.$$

Then, the function $\|\cdot,\dots,\cdot\|' : (X')^n \to \mathbf{R}$ given by

$$\|f_1,\dots,f_n\|' := \sup_{x_i \in X,\ \|x_i\|_2 \le 1} \begin{vmatrix} f_1(x_1) & \dots & f_n(x_1) \\ \vdots & \ddots & \vdots \\ f_1(x_n) & \dots & f_n(x_n) \end{vmatrix}$$

defines an n-norm on X'.

Proof. Similar to the proof of Fact 2 in [6]. □

3 Bounded Multilinear n-Functionals on ℓ^p

In this section, we shall focus on the space of p-summable sequences of real numbers, denoted by $\ell^p = \ell^p_{\mathbb{N}}(\mathbb{R})$, where $1 \le p < \infty$. Recall that a sequence $u := \{u_k\}_{k=1}^\infty$ (of real numbers) belongs ℓ^p space if $\|u\|_p := \left(\sum_{k=1}^\infty |u_k|^p\right)^{1/p} < \infty$. It is known that the dual space of ℓ^p is $\ell^{p'}$ where $\frac{1}{p} + \frac{1}{p'} = 1$.

3.1 Several n-norms on ℓ^p

Using the formula (1.2), ℓ^p may be equipped with the following n-norm:

$$\|x_1,\dots,x_n\|_p^G := \sup_{y_i \in \ell^{p'},\ \|y_i\|_{p'} \le 1} \begin{vmatrix} \sum_{k=1}^\infty x_{1k}y_{1k} & \cdots & \sum_{k=1}^\infty x_{1k}y_{nk} \\ \vdots & \ddots & \vdots \\ \sum_{k=1}^\infty x_{nk}y_{1k} & \cdots & \sum_{k=1}^\infty x_{nk}y_{nk} \end{vmatrix}, \tag{3.1}$$

where p' denotes the dual exponent of p. But there is another formula of n-norm that we can define on ℓ^p, namely

$$\|x_1,\dots,x_n\|_p^H := \left[\frac{1}{n!}\sum_{k_1=1}^\infty \cdots \sum_{k_n=1}^\infty \left| \begin{vmatrix} x_{1k_1} & \cdots & x_{1k_n} \\ \vdots & \ddots & \vdots \\ x_{nk_1} & \cdots & x_{nk_n} \end{vmatrix} \right|^p\right]^{\frac{1}{p}}, \tag{3.2}$$

where $x_i = \{x_{ik}\}_{k=1}^{\infty}$, $i = 1, \ldots, n$. As shown in [12], the two n-norms are equivalent:

$$(n!)^{(1/p)-1}\|x_1,\ldots,x_n\|_p^H \le \|x_1,\ldots,x_n\|_p^G \le (n!)^{1/p}\|x_1,\ldots,x_n\|_p^H.$$

On ℓ^2, both n-norms coincide with the standard n-norm given by (1.3) [6].

Next, one may observe that, by taking the sums and like terms out of the determinant and knowing that there are $n!$ possible ways to do so (see [7]), the determinant on the right hand side of (3.1) can be rewritten as

$$\frac{1}{n!}\sum_{k_1=1}^{\infty}\cdots\sum_{k_n=1}^{\infty}\begin{vmatrix} x_{1k_1} & \cdots & x_{1k_n} \\ \vdots & \ddots & \vdots \\ x_{nk_1} & \cdots & x_{nk_n}\end{vmatrix}\begin{vmatrix} y_{1k_1} & \cdots & y_{1k_n} \\ \vdots & \ddots & \vdots \\ y_{nk_1} & \cdots & y_{nk_n}\end{vmatrix}.$$

By Hölder's inequality, we find that this sum is dominated by

$$\|x_1,\ldots,x_n\|_p^H\,\|y_1,\ldots,y_n\|_{p'}^H.$$

This inspires us to define another n-norm on ℓ^p, namely

$$\|x_1,\ldots,x_n\|_p^I := \sup_{y_i\in\ell^{p'},\,\|y_1,\ldots,y_n\|_{p'}^H\le 1}\begin{vmatrix} \sum_{k=1}^{\infty} x_{1k}y_{1k} & \cdots & \sum_{k=1}^{\infty} x_{1k}y_{nk} \\ \vdots & \ddots & \vdots \\ \sum_{k=1}^{\infty} x_{nk}y_{1k} & \cdots & \sum_{k=1}^{\infty} x_{nk}y_{nk}\end{vmatrix}. \tag{3.3}$$

Theorem 9. *The three n-norms on ℓ^p, namely $\|\cdot,\ldots,\cdot\|_p^I$, $\|\cdot,\ldots,\cdot\|_p^H$, and $\|\cdot,\ldots,\cdot\|_p^G$, are equivalent.*

Proof. By the observation above, we have $\|x_1,\ldots,x_n\|_p^I \le \|x_1,\ldots,x_n\|_p^H$. By Theorem 2.3 of [12], we have $\|x_1,\ldots,x_n\|_p^H \le (n!)^{1/p'}\|x_1,\ldots,x_n\|_p^G$. Now, using the inequality

$$\|y_1,\ldots,y_n\|_{p'}^H \le (n!)^{1/p}\|y_1\|_{p'}\cdots\|y_n\|_{p'}$$

(see Fact 3.1 of [7]), we see that if $\|y_i\|_{p'} \le 1$ for $i = 1,\ldots,n$, then $\|y_1,\ldots,y_n\|_{p'}^H \le (n!)^{1/p}$. Hence we obtain

$$\|x_1,\ldots,x_n\|_p^G \le (n!)^{1/p}\|x_1,\ldots,x_n\|_p^I.$$

The chain of these inequalities shows that the three n-norms are equivalent. ☐

3.2 Multilinear n-functionals on ℓ^p

By a *multilinear n-functional* on a real vector space X we mean a mapping $F : X^n \to \mathbb{R}$ which is linear in each variable. A multilinear n-functional F is *bounded* on an n-normed space $(X, \|\cdot,\ldots,\cdot\|)$ if and only if there exists $K > 0$ such that

$$|F(x_1,\ldots,x_n)| \le K\,\|x_1,\ldots,x_n\| \tag{3.4}$$

for every $x_1,\ldots,x_n \in X$. Note that for a bounded multilinear n-functional F on an n-normed space $(X, \|\cdot,\ldots,\cdot\|)$, we have $F(x_1,\ldots,x_n) = 0$ when $x_1,\ldots,x_n$ are linearly dependent. Moreover, we have the following proposition.

Proposition 10. *If F is a bounded multilinear n-functional on an n-normed space $(X, \|\cdot,\ldots,\cdot\|)$, then F is antisymmetric, that is*

$$F(x_1,\ldots,x_n) = \operatorname{sgn}(\sigma)\,F(x_{\sigma(1)},\ldots,x_{\sigma(n)})$$

for any $x_1,\ldots,x_n \in X$ and any permutation σ of $(1,\ldots,n)$. [Here $\operatorname{sgn}(\sigma) = 1$ *if σ is an even permutation and* $\operatorname{sgn}(\sigma) = -1$ *if σ is an odd permutation.]*

Proof. We give the proof for the case where $n = 2$ and leave the other case to the reader. Here, F is antisymmetric if and only if $F(x_1, x_2) = -F(x_2, x_1)$ for every $x_1, x_2 \in X$. To see this, we observe that

$$F(x_1 + x_2, x_1 + x_2) = F(x_1, x_1) + F(x_1, x_2) + F(x_2, x_1) + F(x_2, x_2).$$

But $F(x, x) = 0$ for every $x \in X$, and so we are done. □

We note that the set X^* of all bounded multilinear n-functionals on $(X, \|\cdot, \dots, \cdot\|)$ forms a vector space. Next, for a bounded multilinear n-functional F, we may define

$$\|F\| := \inf\{K > 0 \,:\, (3.4) \text{ holds}\},$$

or equivalently

$$\|F\| := \sup\{|F(x_1, \dots, x_n)| \,:\, \|x_1, \dots, x_n\| \le 1\}.$$

This formula defines a norm on X^*.

We shall now discuss some multilinear n-functionals on ℓ^p (where $1 \le p < \infty$). Let $Y := \{y_1, \dots, y_n\}$ in $\ell^{p'}$, where p' is the dual exponent of p. We define

$$F_Y(x_1, \dots, x_n) := \frac{1}{n!} \sum_{k_1=1}^{\infty} \cdots \sum_{k_n=1}^{\infty} \begin{vmatrix} x_{1k_1} & \cdots & x_{1k_n} \\ \vdots & \ddots & \vdots \\ x_{nk_1} & \cdots & x_{nk_n} \end{vmatrix} \begin{vmatrix} y_{1k_1} & \cdots & y_{1k_n} \\ \vdots & \ddots & \vdots \\ y_{nk_1} & \cdots & y_{nk_n} \end{vmatrix}, \tag{3.5}$$

for $x_1, \dots, x_n \in \ell^p$. Clearly F_Y is linear in each variable. Further, we have

$$|F_Y(x_1, \dots, x_n)| \le \|x_1, \dots, x_n\|_p^H \|y_1, \dots, y_n\|_{p'}^H,$$

and so F_Y is bounded on $(\ell^p, \|\cdot, \dots, \cdot\|_p^H)$ with $\|F_Y\| \le \|y_1, \dots, y_n\|_{p'}^H$.

For $p = 2$, we have the following fact.

Fact 11 ([6]). Consider the n-normed space $(\ell^2, \|\cdot, \dots, \cdot\|_2^H)$. For fixed linearly independent $Y := \{y_1, \dots, y_n\}$ in ℓ^2, let F_Y be the multilinear n-functional defined as in (3.5). Then F_Y is bounded on $(\ell^2, \|\cdot, \dots, \cdot\|_2^H)$ with

$$\|F_Y\| = \|y_1, \dots, y_n\|_2^H.$$

Proof. From the inequality

$$|F_Y(x_1, \dots, x_n)| \le \|x_1, \dots, x_n\|_2^H \; \|y_1, \dots, y_n\|_2^H,$$

we see that F_Y is bounded with $\|F_Y\| \le \|y_1, \dots, y_n\|_2^H$. Next, if we take

$$x_i := \frac{y_i}{\sqrt[n]{\|y_1, \dots, y_n\|_2^H}}, \quad i = 1, \dots, n,$$

then $\|x_1, \dots, x_n\|_2^H = 1$ and $F_Y(x_1, \dots, x_n) = \|y_1, \dots, y_n\|_2^H$. Hence we conclude that $\|F_Y\| = \|y_1, \dots, y_n\|_2^H$. □

Regarding the n-functional F_Y on $(\ell^p, \|\cdot, \dots, \cdot\|_p^H)$, we have an open problem.

Problem 1. *Compute the exact norm of F_Y in* (3.5)*, especially for $p \neq 2$.*

Problem 2. *Can every bounded multilinear n-functional on ℓ^p be identified by $(y_1, \dots, y_n)$ where $y_i \in \ell^{p'}$, $i = 1, \dots, n$?*

Note that the multilinear n-functional F_Y may be reformulated as

$$F_Y(x_1,\dots,x_n)=\begin{vmatrix}\sum_{k=1}^\infty x_{1k}y_{1k} & \cdots & \sum_{k=1}^\infty x_{1k}y_{nk}\\ \vdots & \ddots & \vdots\\ \sum_{k=1}^\infty x_{nk}y_{1k} & \cdots & \sum_{k=1}^\infty x_{nk}y_{nk}\end{vmatrix}.$$

From this expression, we get the following result.

Fact 12. Let $e_k := (0,\dots,0,1,0,\dots)$ where the k-th term is the only term with value 1. Then, for $k_1,\dots,k_n\in\mathbb{N}$, we have

$$F_Y(e_{k_1},\dots,e_{k_n})=\begin{vmatrix}y_{1k_1} & \cdots & y_{1k_n}\\ \vdots & \ddots & \vdots\\ y_{nk_1} & \cdots & y_{nk_n}\end{vmatrix}.$$

Accordingly, the multiindex sequence $\{F_Y(e_{k_1},\dots,e_{k_n})\}_{k_1,\dots,k_n}$ is p'-summable, in the sense that

$$\left[\frac{1}{n!}\sum_{k_1=1}^\infty\cdots\sum_{k_n=1}^\infty\left\|\begin{vmatrix}y_{1k_1} & \cdots & y_{1k_n}\\ \vdots & \ddots & \vdots\\ y_{nk_1} & \cdots & y_{nk_n}\end{vmatrix}\right\|^{p'}\right]^{\frac{1}{p'}}<\infty.$$

Proof. The first part is straightforward, while the second part follows from the fact that $y_1,\dots,y_n\in\ell^{p'}$ and that the sum is actually equal to $\|y_1,\dots,y_n\|^H_{p'}$. □

The following problem is still open.

Problem 3. *Let F be a bounded multilinear n-functional on ℓ^p. Must the multiindex sequence $\{F(e_{k_1},\dots,e_{k_n})\}_{k_1,\dots,k_n}$ be p'-summable?*

In general, the converse of Fact 11 holds, as follows. (We leave the proof to the reader.)

Proposition 13. *Let $c := \{c_{k_1\cdots k_n}\}_{k_1,\dots,k_n}$ be a multiindex sequence which is antisymmetric and p'-summable. Then, the n-functional F_c given by*

$$F_c(x_1,\dots,x_n):=\sum_{k_1=1}^\infty\cdots\sum_{k_n=1}^\infty x_{1k_1}\cdots x_{nk_n}c_{k_1\cdots k_n}, \tag{3.6}$$

where $x_i := (x_{ik_i})_{k_i=1}^\infty\in\ell^p$ $(i=1,\dots,n)$, is linear in each variable, and is bounded on $(\ell^p,\|\cdot,\dots,\cdot\|^H_p)$ with

$$\|F_c\|\le\left[\frac{1}{n!}\sum_{k_1=1}^\infty\cdots\sum_{k_n=1}^\infty|c_{k_1\cdots k_n}|^{p'}\right]^{1/p'}.$$

Remark 14. Similar to Problem 1, we do not know the exact norm of the n-functional F_c in (3.6)

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