

# Pacific Journal of Mathematics

**PRODUCTS OF FINITELY ADDITIVE SET FUNCTIONS FROM  
ORLICZ SPACES**

VERNON EMIL ZANDER

## PRODUCTS OF FINITELY ADDITIVE SET FUNCTIONS FROM ORLICZ SPACES

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This note establishes two results on products of finitely additive vector-valued set functions from Orlicz spaces. A triple  $(\Omega, \Sigma, \mu)$  is called a charge space if  $\Sigma$  is a ring of subsets of a set  $\Omega$  and the charge  $\mu$  is a finitely additive, non-negative, finite-valued function with domain  $\Sigma$ .

**THEOREM.** For  $(\Omega_i, \Sigma_i, \mu_i)$  ( $i = 1, \dots, n$ ) a family of charge spaces and  $(\Omega, \Sigma, \mu)$  the corresponding product charge space, for  $u$  an  $n$ -linear continuous operator from the product of the Banach spaces  $Z_1, \dots, Z_n$  into a Banach space  $W$ , the function  $v$  defined by  $v(A) = u(v_1(A), \dots, v_n(A))$  for  $A \in \Sigma$  and  $v_i$  from the Orlicz space  $A^\phi(\Omega_i, \Sigma_i, \mu_i, Z_i)$  belongs to the Orlicz space  $A^\phi(\Omega, \Sigma, \mu, W)$ .

For the infinite product case the following result holds:

**THEOREM.** For  $(\Omega_t, \Sigma_t, \mu_t)$  ( $t \in T$ ) a family of probability charge spaces and  $(\Omega, \Sigma, \mu)$  the product probability charge space, for  $u$  an infinitely linear bounded operator on the multiplicative product space  $P_T(A^\phi(\Omega_t, \Sigma_t, \mu_t, Z_t), v_t)$  the function  $v^0$  defined by  $v^0(A) = u(v(A))$  for  $A \in \Sigma$  belongs to the Orlicz space  $A^\phi(\Omega, \Sigma, \mu, W)$ .

These results allow one to develop an integral determined by a product of charges from Orlicz spaces.

In a recent paper by Uhl [5] the Orlicz space  $A^\phi$  of vector-valued finitely additive set functions is investigated. The present paper presents results concerning finite and infinite products of finitely additive vector-valued set functions from the Orlicz spaces

$$A^\phi(\Omega_r, \Sigma_r, \mu_r, X_r)$$

for  $r$  ranging through an index set. The results for a finite product of set functions resemble a generalization of a result by Bogdanowicz [2, Th. 1] for the  $L_p$ -spaces of Lebesgue-Bochner summable functions; and the results for an infinite product of set functions resemble a generalization of a result for the Lebesgue space  $L_1$  by Bogdanowicz and Zander [3, Proposition 5], but the techniques used for the results in the present paper are different.

We shall assume throughout that  $\Phi$  is a convex, nondecreasing function defined on the positive real line such that  $\Phi(0) = 0$  and  $\Phi$  is continuous except for at most one point, after which the function must be identically infinite. We shall also assume throughout that

the function  $\Phi$  satisfies the following growth condition:

$$\Phi(xy) \leq M\Phi(x)\Phi(y)$$

for all  $x, y \geq 0$ , where  $M$  is a positive constant. (This growth condition is called the  $\Delta'$ -condition (see [4, p. 29]).)

REMARK 1. Each of the functions  $f(x) = x^\alpha$  with  $q \geq 1$  and

$$g(x) = x^\alpha(\log^+ x + 1)$$

with  $\alpha > 1$  satisfies the  $\Delta'$ -condition with constant 1, and each is a candidate for the function  $\Phi$ .

Let  $\Omega$  be any set,  $\Sigma$  a ring of subsets of  $\Omega$ , and  $\mu$  a nonnegative, real-valued, finitely additive function with domain  $\Sigma$ . The associated triple  $(\Omega, \Sigma, \mu)$  shall be called a charge space. If, further,  $\Omega \in \Sigma$  and  $\mu(\Omega) = 1$  then the triple  $(\Omega, \Sigma, \mu)$  shall be called a probability charge space.

For  $(\Omega, \Sigma, \mu)$  a charge space and  $Z$  a Banach space denote by  $A^0(\mu, Z)$  the space of all finitely additive functions  $v$  from the ring  $\Sigma$  into the space  $Z$  which satisfy the following conditions: (i)  $v$  vanishes on the  $\mu$ -null sets, (ii)  $I_\phi(v/k) \leq 1$  for some positive  $k$ , where the function  $I_\phi$  is defined by the following expression:

$$I_\phi(v) = \sup \Sigma \{ \Phi(|v(A)|/\mu(A))\mu(A) : A \in \mathcal{F} \}$$

where the supremum is taken over all finite families  $\mathcal{F}$  of disjoint sets from the ring  $\Sigma$ . This definition is recently given by Uhl [5, p. 24], and is due originally to Bochner [1, p. 778]. By Theorem 11 of [5] the functional  $N_\phi$  defined by

$$N_\phi(v) = \inf \{ k > 0 : I_\phi(v/k) \leq 1 \}$$

is a norm under which the space  $A^0(\mu, Z)$  is Banach space.

We shall use the following notation: Let  $T_i$  be a family of subsets from an abstract set  $X_i$ , for  $i = 1, \dots, n$ . By  $T_1 \times \dots \times T_n$  we shall mean the family of all sets of the form  $A_1 \times \dots \times A_n$  where  $A_i \in T_i$  for  $i = 1, \dots, n$ .

For charge spaces  $(\Omega_i, \Sigma_i, \mu_i)$  ( $i = 1, \dots, n$ ) define the triple  $(\Omega, \Sigma_0, \mu)$  by  $\Omega = \Omega_1 \times \dots \times \Omega_n$ ,  $\Sigma = \Sigma_1 \times \dots \times \Sigma_n$ ,  $\Sigma_0$  is the ring generated from the prering  $\Sigma$ , and  $\mu(A) = \mu_1(A_1) \dots \mu_n(A_n)$  for  $A \in \Sigma$ . It is easy to see that  $(\Omega, \Sigma_0, \mu)$  is a charge space.

DEFINITION. For  $\mathcal{F}$  a finite family of disjoint sets from the prering  $\Sigma$  and for  $i$  between 1 and  $n$  let  $\mathcal{F}_i$  denote the family of all  $i$ -th coordinate sets  $A_i$ , where  $A_1 \times \dots \times A_i \times \dots \times A_n \in \mathcal{F}$ , and let

$\mathcal{F}_i^r$  denote the refinement of  $\mathcal{F}_i$  consisting of the finite family of disjoint sets from  $\Sigma_i$  whose union is the same as that of all sets from  $\mathcal{F}_i$ . That is, if  $\mathcal{F}_i = \{B_1, \dots, B_m\}$ , and if  $B'_j = \Omega_i \setminus B_j$  then  $\mathcal{F}_i^r$  is the set of all intersections  $C_1 \cap \dots \cap C_m$  where each  $C_j$  is  $B_j$  or  $B'_j$  and at least one  $C_j$  is  $B_j$ . By the  $\mathcal{F}$ -product we shall mean the corresponding finite family of disjoint sets  $\mathcal{F}_1^r \times \dots \times \mathcal{F}_n^r$  from the prering  $\Sigma$ . We shall denote this family by  $(\mathcal{F})$ .

LEMMA 1. For  $v \in A^\phi(\mu, Z)$  we have the relation

$$I_\phi(v) = \sup \Sigma \{ \Phi(|v(A)|/\mu(A))\mu(A) : A \in (\mathcal{F}) \}$$

where the supremum is taken over all finite families  $\mathcal{F}$  of disjoint sets from  $\Sigma$ .

*Proof.* Let  $a$  denote the right side of the above relation. Then  $I_\phi(v) \geq a$  since an  $\mathcal{F}$ -product is a particular finite disjoint family from  $\Sigma$ . Let  $B, C$  be disjoint sets from  $\Sigma$ , and put  $A = B \cup C$ . Then the relation  $I_\phi(v) \leq a$  follows from the positivity of values of the function  $\Phi$  and from the relation

$$\Phi(|v(A)|/\mu(A))\mu(A) \leq \Phi(|v(B)|/\mu(B))\mu(B) + \Phi(|v(C)|/\mu(C))\mu(C)$$

which in turn follows from the convexity of the function  $\Phi$ .

Let  $Z_i, W$  ( $i = 1, \dots, n$ ) be Banach spaces and let  $u$  be an  $n$ -linear continuous operator from the product of the spaces  $Z_1, \dots, Z_n$  into the space  $W$ . Denote the norms in the above spaces by  $|\cdot|$ .

THEOREM 2. If  $v_i \in A^\phi(\mu_i, Z_i)$  for  $i = 1, \dots, n$  then  $v \in A^\phi(\mu, W)$ , where

$$v(A_1 \times \dots \times A_n) = u(v_1(A_1), \dots, v_n(A_n)) \text{ for } A \in \Sigma.$$

*Proof.* We shall establish that  $I_\phi(v/k) \leq 1$  for some positive  $k$ . Assume throughout that the  $\Delta'$ -constant  $M \geq 1$ . Put

$$w_j(\cdot) = |v_j(\cdot)|/N_\phi(v_j)$$

and  $b = M^n |u| N_\phi(v_1) \dots N_\phi(v_n)$ , and let  $\mathcal{F}$  be a finite family of disjoint sets from  $\Sigma$ . Then we have the following estimates:

$$\begin{aligned} & \Sigma \{ \Phi(|v(A)|/b\mu(A))\mu(A) : A \in (\mathcal{F}) \} \\ & \leq \Sigma \left\{ \Phi \left( \prod_{k=1}^n w_k(A_k) / M \mu_k(A_k) \right) \mu(A) : A \in (\mathcal{F}) \right\} \\ & \leq \Sigma \left\{ \left[ \prod_{k=1}^n M \Phi(w_k(A_k) / M \mu_k(A_k)) \right] \mu(A) : A \in (\mathcal{F}) \right\}. \end{aligned}$$

Noting that  $\Phi(a/M) \leq \Phi(a)/M$  for  $a \geq 0$  since  $\Phi$  is convex and  $M \geq 1$ , we conclude that

$$\begin{aligned} & \Sigma\{\Phi(|v(A)|/b\mu(A))\mu(A): A \in (\mathcal{F})\} \\ & \leq \prod_{k=1}^n \{\Sigma\Phi(w_k(A)/\mu_k(A))\mu_k(A): A \in \mathcal{F}_k^r\} \\ & \leq I_\phi(w_1) \cdots I_\phi(w_n) \leq 1. \end{aligned}$$

By taking the appropriate supremum, we see that  $I_\phi(v/b) \leq 1$ . From this it can easily be seen that  $v \in A^\phi(\mu, W)$ .

We shall now consider infinite products of vector-valued finitely additive set functions.

Let  $T$  be an arbitrary index set, let  $(\Omega_t, \Sigma_t, \mu_t)$  ( $t \in T$ ) be a family of probability charge spaces and let  $(\Omega, \Sigma, \mu)$  be the product space (i.e.,  $\Omega = X_T \Omega_t$ ,  $\Sigma$  is the family of all finite disjoint unions of sets of the form  $A = X_T A_t$  where  $A_t \in \Sigma_t$  and  $A_t \neq \Omega_t$  for at most a finite number of indices  $t \in T$ , and  $\mu(A) = \prod_T \mu_t(A_t)$  for all  $A \in \Sigma$ .) It is clear that the triple  $(\Omega, \Sigma, \mu)$  is a probability charge space.

Let  $Y, Z_t$  ( $t \in T$ ),  $W$  be Banach spaces, let  $z'_t \in Z_t$  each be of unit norm, and let  $Z' = P_T(Z_t, z'_t)$  be the corresponding multiplicative product space. That is,  $P_T(Z_t, z'_t)$  is the set of all  $z = (z_t)_T$  such that  $z_t \in Z_t$  for  $t \in T$  and  $\Sigma_T |z_t - z'_t| < \infty$ . Define a functional  $d$  by

$$d(y, z) = \Sigma_T |y_t - z_t|$$

for all  $y, z \in Z'$ . In [3] it is shown that the space  $(Z', d)$  is a complete metric space. It is easy to see that the space  $Z'$  is also an affine subspace of the linear space  $X_T Z_t$ , and if  $T$  is uncountable the metric  $d$  cannot be extended to a metric on the space  $X_T Z_t$ .

An operator  $u$  mapping the space  $Z'$  into the space  $W$  shall be called infinitely linear and bounded if  $u$  is linear on each coordinate space  $Z_t$  separately, for all  $t \in T$ , and if there is a positive constant  $c$  such that  $|u(z)| \leq c \Pi_T |z_t|$  for all  $z \in Z'$ . Let  $\|u\|$  denote the smallest of all such constants. Let  $L(Z'; W)$  denote the space of all such bounded infinitely linear operators. In [3] it is shown that the space  $L(Z'; W)$  under the functional  $\| \cdot \|$  is a Banach space.

In order to make the next definition we must further restrict the function  $\Phi$  so that  $\Phi(1) = 1$  and the  $\Delta'$ -constant  $M = 1$ . These conditions are the results of applying a version of Lemma 13 of [5], modified to assume the  $\Delta'$ -condition. Since the functions  $g$  and  $f$  from Remark 1 are nontrivial examples of functions which satisfy these conditions, the additional conditions are not as restrictive as they originally appeared to be.

Select  $v'_t \in A^\phi(\mu_t, Z_t)$  such that  $v'_t(\Omega_t) = z'_t$  and  $N_\phi(v'_t) = 1$ , and let

$P_T(A^\circ(\mu_i, Z_i), v_i)$  be the corresponding multiplicative product space. We remark that from Lemma 13 of [5] it follows that  $v(\Omega) \in Z'$  for all  $v \in P_T(A^\circ(\mu_i, Z_i), v_i)$ .

For the infinite product ring  $\Sigma$  we need some notation similar to the  $\mathcal{F}$ -product concept for the finite case. With this in mind let  $\mathcal{F}$  be a finite family of disjoint sets from the infinite product ring  $\Sigma$ , let the families  $\mathcal{F}_t$  and  $\mathcal{F}_t^r$  be defined as in the finite product case, and define the  $\mathcal{F}$ -product as the corresponding finite family of disjoint sets

$$X_T \mathcal{F}_t^r = \{A = X_T A_t : A_t \in \mathcal{F}_t^r \text{ for all } t \in T\}$$

from the ring  $\Sigma$ . Again we shall denote the  $\mathcal{F}$ -product by  $(\mathcal{F})$ . (It follows from the definition of  $\Sigma$  and properties of a ring that  $(\mathcal{F})$  consists of a finite number of disjoint sets from  $\Sigma$ .)

**THEOREM 3.** *If  $v \in P_T(A^\circ(\mu_i, Z_i), v_i)$  and  $u \in L(Z'; W)$  then the function  $v^\circ$  defined by  $v^\circ(A) = u(v(A))$  for all  $A \in \Sigma$  belongs to the space  $A^\circ(\mu, W)$ .*

*Proof.* It is clear that the function  $v^\circ$  is finitely additive on  $\Sigma$ , and from the estimate  $|v^\circ(A)| \leq \|u\| |\Pi_T v_i(A_t)|$  for all  $A \in \Sigma$  it is clear that  $v(A) = 0$  when  $\mu(A) = 0$ . To establish that  $I_\phi(v/k) \leq 1$  for some constant  $k$ , put  $w_i(\cdot) = |v_i(\cdot)|/N_\phi(v_i)$  and  $b = \|u\| \Pi_T N_\phi(v_i)$  and let  $\mathcal{F}$  be a finite family of disjoint sets from  $\Sigma$ . Applying Lemma 1, which is clearly valid here, we get the following estimates:

$$\begin{aligned} & \Sigma \{ \Phi(|v^\circ(A)|/b \mu(A)) \mu(A) : A \in (\mathcal{F}) \} \\ & \leq \Sigma \{ \Phi(\Pi_S w_i(\Omega_i) \Pi_S (w_i(A_i)/\mu_i(A_i))) \mu(A) : A \in (\mathcal{F}) \} \\ & \leq \Sigma \{ \Pi_S \Phi(w_i(A_i)/\mu_i(A_i)) \mu(A) : A \in (\mathcal{F}) \} \\ & \leq \Pi_S \{ \Sigma \{ \Phi(w_i(A)/\mu_i(A)) \mu_i(A) : A \in \mathcal{F}_i^r \} \} \\ & \leq \Pi_S I_\phi(w_i) \leq 1. \end{aligned}$$

Hence  $v^\circ \in A^\circ(\mu, W)$  and  $N_\phi(v^\circ) \leq \|u\| \Pi_T N_\phi(v_i)$ .

**REMARK 2.** The results in this note remain valid if all rings are relaxed to prerings, with no changes needed in the above proofs to establish this.

**REMARK 3.** Forthcoming papers will discuss the other formulations of the Fubini theorems for Orlicz spaces in terms of a countably additive nonnegative finite valued set function (called a volume) defined on a prerings. The prerings, volume combination appears to be the most natural context in which to discuss the Fubini theorems; that it is also a valid context follows from the work of Bogdanowicz,

which develops an integration theory based upon the prering and volume. See [2] for a suitable bibliography.

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