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The Alexandroff property for vector lattices of real-valued functions

By WOLFGANG ADAMSKI (München)

Abstract. If X is a topological space, then a classical result of A.D. Alexandroff states that the class of σ-smooth linear functionals defined on the vector lattice of all bounded continuous real-valued functions on X is sequentially closed with respect to pointwise convergence. It is the aim of this note to investigate this property for arbitrary vector lattices of real-valued functions.

1. Introduction

In 1943 A.D. Alexandroff proved that the class of σ-smooth linear functionals defined on the vector lattice of all bounded continuous real-valued functions on a topological space X is sequentially closed with respect to pointwise convergence. In this note we study this property for arbitrary vector lattices of real-valued functions defined on an abstract set X. We first give a sufficient condition for this so-called Alexandroff property. As an application of this general result we show that, for an arbitrary δ-lattice $\mathcal{L}$ of subsets of X, the vector lattice of bounded $\mathcal{L}$-continuous functions has the Alexandroff property. In particular, if $\mathcal{L}$ is the family of closed subsets of a topological space X, we obtain Alexandroff's classical theorem. On the other hand, if X is a metric space then it is shown by an example that the vector lattices of bounded uniformly continuous functions and bounded Lipschitz continuous functions on X do not have the Alexandroff property, in general.

Now we fix the notation. $\mathbb{N}$ denotes the set of positive integers. The set $\mathbb{R}$ of real numbers is always assumed to be equipped with the Euclidean topology.

Let X be an arbitrary set and let $\mathcal{P}(X)$ be the power set of X. 1_Q denotes the indicator function of a set $Q \in \mathcal{P}(X)$. If f is a function defined on X then we write $f \mid Q$ for the restriction of f onto the subset Q of X.

Let $\mathcal{L}$ be a subset of $\mathcal{P}(X)$. $\mathcal{L}$ is said to be a *lattice* if $\emptyset, X \in \mathcal{L}$ and $\mathcal{L}$ is closed under finite intersections and finite unions. A lattice that is closed under countable intersections is called a δ-*lattice*. The lattice $\mathcal{L}$ is said to be *normal* if, for any two disjoint sets $L_1, L_2 \in \mathcal{L}$, there exist disjoint sets $K_1, K_2 \in \mathcal{L}' := \{X - L : L \in \mathcal{L}\}$ such that $L_i \subset K_i$ for $i = 1, 2$. Furthermore, the lattice $\mathcal{L}$ is called *countably paracompact* if, for every decreasing sequence $(L_n) \subset \mathcal{L}$ with empty intersection, there exists a sequence (G_n) of $\mathcal{L}'$-sets with empty intersection such that $L_n \subset G_n$ for all $n \in \mathbb{N}$. An $\mathcal{L}$-step function is a finite linear combination of members of $\{1_L : L \in \mathcal{L}\}$.

For a sequence (f_n) of real-valued functions on X we write $f_n \downarrow 0$ if (f_n) is decreasing (i.e. $f_{n+1} \leq f_n$ for all $n \in \mathbb{N}$) and $\lim f_n(x) = 0$ for every $x \in X$. An integral $\int f d\mu$ is usually written as $\mu(f)$.

If X is a topological space then $\mathcal{C}(X)$ $[\mathcal{C}^b(X)]$ denotes the vector lattice of all [bounded] continuous real-valued functions on X, and we write $\mathcal{F}(X), \mathcal{K}(X), \mathcal{B}(X)$ for the collection of all closed, compact, Borel sets in X, respectively.

2. The main results

Let X be an arbitrary nonvoid set and $E \subset \mathbb{R}^X$ a vector lattice of real-valued functions on X. E^* denotes the algebraic dual of E, i.e. E^* is the family of all real-valued linear functions (= linear functionals) defined on E. In addition, let $E_+ := \{f \in E : f \geq 0\}$.

Definition. $\Phi \in E^*$ is said to be

(i) *order-bounded* if $\sup\{|\Phi(h)| : h \in E, |h| \leq f\} < \infty$ for all $f \in E_+$;

(ii) *nonnegative* if $\Phi(f) \geq 0$ whenever $f \in E_+$;

(iii) σ-*smooth* if $\lim \Phi(f_n) = 0$ for every sequence (f_n) in E with $f_n \downarrow 0$.

The relations between these concepts are described in

Lemma 2.1 ([7], 2.3)**.** *(a) Every σ-smooth $\Phi \in E^*$ is order-bounded.*

(b) $\Phi \in E^*$ is order-bounded iff there are nonnegative $\Phi_1, \Phi_2 \in E^*$ such that $\Phi = \Phi_1 - \Phi_2$. If, in addition, Φ is σ-smooth then Φ_1, Φ_2 can be chosen to be σ-smooth, too.

Define $\Lambda(E) := \{\Phi \in E^* : \Phi \text{ is order-bounded}\}$, $\Lambda_\sigma(E) := \{\Phi \in \Lambda(E) : \Phi \text{ is } \sigma\text{-smooth}\}$, $\Gamma(E) := \{\Phi \in E^* : \Phi \text{ is nonnegative}\}$ and $\Gamma_\sigma(E) := \{\Phi \in \Gamma(E) : \Phi \text{ is } \sigma\text{-smooth}\}$.

In view of 2.1, $\Gamma(E) \subset \Lambda(E)$ and $\Lambda_\sigma(E) = \{\Phi \in E^* : \Phi \text{ is } \sigma\text{-smooth}\}$.

E is said to be a *Daniell lattice* ([1]) if $\Gamma(E) = \Gamma_\sigma(E)$. It is obvious that E is a Daniell lattice iff $\Lambda(E) = \Lambda_\sigma(E)$.

If X is a topological space, then a classical result of A.D. Alexandroff (see [2], Theorem 19.3, or [10], Theorem II.19) states that $\Lambda_\sigma(\mathcal{C}^b(X))$ is sequentially closed in $\Lambda(\mathcal{C}^b(X))$ with respect to pointwise convergence. In the following we will investigate this property for arbitrary vector lattices of real-valued functions.

Definition. We say that the vector lattice $E \subset \mathbb{R}^X$ has the *Alexandroff property* if, for every sequence (Φ_n) in $\Lambda_\sigma(E)$ and any $\Phi \in \Lambda(E)$, $\lim \Phi_n(f) = \Phi(f)$ for all $f \in E$ implies $\Phi \in \Lambda_\sigma(E)$.

It is trivial that every Daniell lattice has the Alexandroff property. A deeper result is given in

Proposition 2.2. *E has the Alexandroff property provided that E satisfies the following condition:*

$$\text{(2.1)} \qquad \textit{If } f_1, f_2, \ldots \in E_+ \textit{ and } \sum_{k\in\mathbb{N}} f_k \in E, \textit{ then } \sum_{k\in A} f_k \in E \textit{ for all } A \in \mathcal{P}(\mathbb{N}).$$

Proof. Let $(\Phi_n) \subset \Lambda_\sigma(E)$ and $\Phi \in \Lambda(E)$ be such that $\lim \Phi_n(f) = \Phi(f)$ holds true for every $f \in E$. To prove the σ-smoothness of Φ it suffices to show $\Phi(\sum_{k\in\mathbb{N}} f_k) = \sum_{k\in\mathbb{N}} \Phi(f_k)$ for every sequence (f_k) in E_+ with $\sum_{k\in\mathbb{N}} f_k \in E$. Let such a sequence (f_k) be given. In view of (2.1), we can define $\mu_n(A) := \Phi_n(\sum_{k\in A} f_k)$ and $\mu(A) := \Phi(\sum_{k\in A} f_k)$ for $A \in \mathcal{P}(\mathbb{N})$ and $n \in \mathbb{N}$. (μ_n) is a sequence of finite signed measures on $\mathcal{P}(\mathbb{N})$ satisfying $\lim \mu_n(A) = \mu(A) \in \mathbb{R}$ for all $A \subset \mathbb{N}$. By Nikodym's theorem (see [6], III.7.4), μ is also a signed measure on $\mathcal{P}(\mathbb{N})$. This implies $\sum_{k=1}^{n} \Phi(f_k) = \Phi(\sum_{k=1}^{n} f_k) = \mu(\{1,\ldots,n\}) \to \mu(\mathbb{N}) = \Phi(\sum_{k\in\mathbb{N}} f_k)$, i.e. $\Phi(\sum_{k\in\mathbb{N}} f_k) = \sum_{k\in\mathbb{N}} \Phi(f_k)$. $\square$

If $(X, \mathcal{A}, \mu)$ is a measure space and $p \in [1, \infty)$, then it is an immediate consequence of 2.2 that $E := \mathcal{L}_p(X, \mathcal{A}, \mu)$ has the Alexandroff property.

We will now give another example of a vector lattice with the Alexandroff property. For this purpose consider a δ-lattice $\mathcal{L}$ of subsets of X. A real-valued function f on X is said to be $\mathcal{L}$-*continuous* if $f^{-1}(F) \in \mathcal{L}$ for all closed subsets F of $\mathbb{R}$. Note that a function $f \in \mathbb{R}^X$ is $\mathcal{L}$-continuous iff the sets $\{f \geq t\}$ and $\{f \leq t\}$ belong to $\mathcal{L}$ for all $t \in \mathbb{R}$. Define $\mathcal{C}(\mathcal{L}) := \{f \in \mathbb{R}^X : f \text{ is } \mathcal{L}\text{-continuous}\}$ and $\mathcal{C}^b(\mathcal{L}) := \{f \in \mathcal{C}(\mathcal{L}) : f \text{ is bounded}\}$. Then $\mathcal{C}(\mathcal{L})$ and $\mathcal{C}^b(\mathcal{L})$ are vector lattices containing the constants [3].

Examples 2.3. (a) Let $\mathcal{L}$ be a σ-algebra in X. Then $\mathcal{C}(\mathcal{L})$ $[\mathcal{C}^b(\mathcal{L})]$ is the family of all [bounded] $\mathcal{L}$-measurable real-valued functions on X.

(b) If X is a topological space, then $\mathcal{C}(X) = \mathcal{C}(\mathcal{F}(X))$ and $\mathcal{C}^b(X) = \mathcal{C}^b(\mathcal{F}(X))$.

Proposition 2.4. *$\mathcal{C}^b(\mathcal{L})$ has the Alexandroff property.*

Proof. We show that $E := \mathcal{C}^b(\mathcal{L})$ satisfies (2.1). Let $(f_k) \subset E_+$ with $f := \sum_{k\in\mathbb{N}} f_k \in E$ be given. We must prove $\sum_{k\in A} f_k \in E$ for every infinite subset A of $\mathbb{N}$. If $\mathbb{N} - A$ is finite, then $\sum_{k\in A} f_k = f - \sum_{k\in\mathbb{N}-A} f_k \in E$. Thus we assume that both A and $\mathbb{N} - A$ are infinite. Let $A = \{n_1, n_2, \dots\}$ with $n_1 < n_2 < \dots$ and $\mathbb{N} - A = \{r_1, r_2, \dots\}$ with $r_1 < r_2 < \dots$. For any $t \in \mathbb{R}$ we obtain $\left\{\sum_{k\in A} f_k \leq t\right\} = \bigcap_{m\in\mathbb{N}} \left\{\sum_{k=1}^{m} f_{n_k} \leq t\right\} \in \mathcal{L}$ and

$$\left\{\sum_{k\in A} f_k \geq t\right\} = \left\{\sum_{k\in\mathbb{N}-A} f_k - f \leq -t\right\} = \bigcap_{m\in\mathbb{N}} \left\{\sum_{k=1}^{m} f_{r_k} - f \leq -t\right\} \in \mathcal{L}.$$

Hence $\sum_{k\in A} f_k$ is $\mathcal{L}$-continuous. □

Remark 2.5. An analysis of the proof of 2.4 reveals that also $\mathcal{C}(\mathcal{L})$ has the Alexandroff property. However, we know from [1], Corollary 2, that $\mathcal{C}(\mathcal{L})$ is even a Daniell lattice.

From 2.3 and 2.4 we deduce

Corollary 2.6. (a) *If $\mathcal{L}$ is a σ-algebra in X, then the vector lattice of all bounded $\mathcal{L}$-measurable real-valued functions on X has the Alexandroff property.*

(b) *If X is a topological space, then the vector lattice of all bounded continuous real-valued functions on X has the Alexandroff property.*

For a lattice $\mathcal{L}$ of subsets of X we denote by $\mathrm{MR}(\mathcal{L})$ the family of all bounded real-valued $\mathcal{L}$-regular finitely additive measures defined on $\alpha(\mathcal{L})$, the algebra generated by $\mathcal{L}$. Moreover, let $\mathrm{MR}(\sigma, \mathcal{L}) := \{\mu \in \mathrm{MR}(\mathcal{L}) : \mu \text{ is } \sigma\text{-additive}\}$. According to [8] (or [9]), a normal δ-lattice $\mathcal{L}$ is called an *Alexandrov lattice* if, for every sequence (μ_n) in $\mathrm{MR}(\sigma, \mathcal{L})$ and any $\mu \in \mathrm{MR}(\mathcal{L})$, $\lim \mu_n(f) = \mu(f)$ for all $f \in \mathcal{C}^b(\mathcal{L})$ implies $\mu \in \mathrm{MR}(\sigma, \mathcal{L})$.

It follows from 2.4 via the Alexandroff representation theorem ([2], Theorem 7.1 combined with Theorem 10.1) that every countably paracompact normal δ-lattice is an Alexandrov lattice. (Observe that it is not the complete normality of the lattice but the weaker property of countable paracompactness that is needed in the proof of [2], Theorem 10.1.) The following example shows that the countable paracompactness is not necessary for a normal δ-lattice to be Alexandrov.

Example 2.7. Let $\mathcal{L}$ be a δ-lattice of subsets of X such that

(α) $\mathcal{L} - \{\emptyset\}$ is closed under finite intersections and

(β) $\mathcal{L}$ is not countably paracompact.

(Note that in case $X = \mathbb{N}$, $\mathcal{L} := \{\{x \in \mathbb{N} : x \geq n\} : n \in \mathbb{N}\} \cup \{\emptyset\}$ is a δ-lattice satisfying the conditions (α) and (β).)

In view of (α), $\mathcal{L}$ is normal vacuously. To prove that $\mathcal{L}$ is an Alexandrov lattice we need two auxiliary results.

2.7.1. *Let $\mu \in \mathrm{MR}(\mathcal{L})$ be nonnegative and nonzero. Then*

(1) $\mu(G) = 0$ *for all* $G \in \mathcal{L}' - \{X\}$*;*
(2) μ *is 2-valued and not* σ*-additive.*

Proof. (1) Let $G \in \mathcal{L}' - \{X\}$ be given. For any $L \in \mathcal{L}$ with $L \subset G$, we have $L = \emptyset$ by (α) and hence $\mu(G) = \sup\{\mu(L) : L \in \mathcal{L}, L \subset G\} = 0$.

(2) If $A \in \alpha(\mathcal{L})$ satisfies $\mu(A) > 0$, then $\mu(A) = \inf\{\mu(G) : A \subset G \in \mathcal{L}'\} = \mu(X)$ where the last equality holds by (1). Thus μ is 2-valued. In view of (β), there exists a sequence (L_n) of nonvoid $\mathcal{L}$-sets decreasing to $\emptyset$. Then $X = \bigcup_{n \in \mathbb{N}} G_n$ where $G_n := X - L_n \in \mathcal{L}' - \{X\}$ and hence $\mu(G_n) = 0$, $n \in \mathbb{N}$, by (1). Consequently, μ is not σ-additive.

2.7.2. *If $\mu_1, \mu_2 \in \mathrm{MR}(\mathcal{L})$ are nonnegative with $\mu_1(X) = \mu_2(X)$, then $\mu_1 = \mu_2$.*

Proof. W.l.o.g. let $\mu_1(X) = \mu_2(X) > 0$. Assume $\mu_1 \neq \mu_2$. Then $\mu_1(A) \neq \mu_2(A)$, say $\mu_1(A) < \mu_2(A)$ for some $A \in \alpha(\mathcal{L})$. From 2.7.1 (2) we infer $\mu_1(A) = 0$, $\mu_2(A) = \mu_2(X) > 0$. Since μ_1 is $\mathcal{L}$-regular, $\mu_1(G) = 0$ for some $G \in \mathcal{L}'$ with $A \subset G$. Then $G \neq X$ and hence $\mu_2(G) = 0$ by 2.7.1 (1) which contradicts $\mu_2(A) > 0$.

2.7.3. *$\mathcal{L}$ is an Alexandrov lattice.*

Proof. Let $(\mu_n) \subset \mathrm{MR}(\sigma, \mathcal{L})$ and $\mu \in \mathrm{MR}(\mathcal{L})$ satisfy $\lim \mu_n(f) = \mu(f)$ for all $f \in \mathcal{C}^b(\mathcal{L})$. From 2.7.1 (2) we infer, using the Jordan decomposition, $\mu_n = 0$ for all $n \in \mathbb{N}$ and consequently $\mu(f) = 0$ for all $f \in \mathcal{C}^b(\mathcal{L})$. In particular, for $f = 1$, we obtain $\mu(X) = 0$, i.e. $\mu^+(X) = \mu^-(X)$. Now 2.7.2 implies $\mu^+ = \mu^-$. Thus $\mu = 0 \in \mathrm{MR}(\sigma, \mathcal{L})$. $\square$

For the case of a σ-algebra $\mathcal{L}$ it is an immediate consequence of Nikodym's theorem ([6], III.7.4), combined with the Daniell–Stone theorem ([4], Satz 39.4), that the vector lattice of all $\mathcal{L}$-step functions has the Alexandroff property. However, if $\mathcal{L}$ is only an algebra, then the vector lattice of all $\mathcal{L}$-step functions does not have the Alexandroff property, in general, as the following example shows.

Example 2.8. Let X be the set of nonnegative integers, $\mathcal{L} := \{L \subset X : L \text{ or } X - L \text{ is finite}\}$ and E the family of all $\mathcal{L}$-step functions. For $L \in \mathcal{L}$, define $\mu(L) := 0$ or 1 according as L is finite or not. Then μ is a finitely additive measure on the algebra $\mathcal{L}$. For $f \in E$, say $f = \sum_{i=1}^{k} \alpha_i 1_{L_i}$ with $\alpha_i \in \mathbb{R}$ and $L_i \in \mathcal{L}$ for $i = 1, \ldots, k$, define $\Phi(f) := \sum_{i=1}^{k} \alpha_i \mu(L_i)$ and $\Phi_n(f) := \frac{1}{n} \sum_{j=0}^{n-1} f(j)$, $n \in \mathbb{N}$. Then $(\Phi_n) \subset \Gamma_\sigma(E)$ and $\lim \Phi_n(f) = \Phi(f)$ for every $f \in E$. However, Φ is not σ-smooth, since μ fails to be σ-additive (cf. [4], Beispiel 39.4).

Next we will present two further examples of vector lattices that do not have the Alexandroff property, in general. For this purpose we consider a metric space (X, d). Recall that a real-valued function f on X is *d-Lipschitz continuous* if there exists a constant $c \in [0, \infty)$ such that $|f(x) - f(y)| \leq c d(x, y)$ for all $x, y \in X$. It is proved in [5] that the collection $\mathrm{BL}(X, d)$ of all bounded d-Lipschitz continuous functions on X forms a vector lattice. It is a sublattice of the vector lattice $U^b(X, d)$ of all bounded uniformly d-continuous real-valued functions on X. It will be shown that neither $U^b(X, d)$ nor $\mathrm{BL}(X, d)$ do have the Alexandroff property, in general.

Example 2.9. Let $Y := \mathbb{R} \cup \{\omega\}$ be the one-point compactification of the real line $\mathbb{R}$. Since Y is metrizable, there exists a metric d on Y compatible with the topology of Y. Then $(\mathbb{R}, d)$ is a separable metric space that is not complete.

For $n \in \mathbb{N}$, let P_n be the normal distribution with expectation 0 and variance n. Defining $Q_n(B) := P_n(B \cap \mathbb{R})$ for $B \in \mathcal{B}(Y)$ and $n \in \mathbb{N}$, we obtain a sequence (Q_n) of probability measures on $\mathcal{B}(Y)$. If $K \in \mathcal{K}(\mathbb{R})$, then K has finite Lebesgue measure $\lambda(K)$ and hence $P_n(K) = (2\pi n)^{-1/2} \int_K \exp\left(-\frac{x^2}{2n}\right) dx \le (2\pi n)^{-1/2} \lambda(K) \to 0$ for $n \to \infty$ which implies $\limsup Q_n(F) \le 1_F(\omega)$ for all $F \in \mathcal{F}(Y) = \mathcal{K}(Y)$. Thus, by the portmanteau theorem ([5], 11.1.1),

$$\lim Q_n(f) = f(\omega) \quad \text{for all } f \in \mathcal{C}(Y). \tag{2.2}$$

Now define $T(f) := f|\mathbb{R}$ for $f \in \mathcal{C}(Y)$. T is a bijection from $\mathcal{C}(Y)$ onto $U^b(\mathbb{R}, d)$. From (2.2) we infer $P_n(T(f)) = Q_n(f) \to f(\omega)$ for $f \in \mathcal{C}(Y)$, hence $P_n(g) = Q_n(T^{-1}(g)) \to \Phi(g) := T^{-1}(g)(\omega)$ for $g \in U^b(\mathbb{R}, d)$. Observe that $P_n \in \Gamma_\sigma(U^b(\mathbb{R}, d))$, $n \in \mathbb{N}$, and $\Phi \in \Gamma(U^b(\mathbb{R}, d))$. To prove that $U^b(\mathbb{R}, d)$ fails to have the Alexandroff property, it suffices to show $\Phi \notin \Gamma_\sigma(U^b(\mathbb{R}, d))$. For this purpose, define $g_n(t) := \max\left(0, \min\left(1, \frac{1}{n}|t|\right)\right)$ for $t \in \mathbb{R}$ as well as $f_n(x) := g_n(x)$ for $x \in \mathbb{R}$ and $f_n(\omega) := 1$, $n \in \mathbb{N}$. It is easy to see that f_n is continuous and so $g_n = T(f_n) \in U^b(\mathbb{R}, d)$. Since $g_n \downarrow 0$ and $\Phi(g_n) = f_n(\omega) = 1$ for every $n \in \mathbb{N}$, Φ is not σ-smooth.

Furthermore, by [5], 11.2.4, there exists a function $h_n \in \mathrm{BL}(Y, d)$ satisfying $h_n \ge 0$ and $|f_n(y) - h_n(y)| \le 2^{-n}$ for all $y \in Y$. Then $v_n := \min(h_1, \ldots, h_n) \in \mathrm{BL}(Y, d)$ and $T(v_n) = v_n|\mathbb{R} \downarrow 0$. On the other hand, $h_n(\omega) \ge f_n(\omega) - 2^{-n} \ge \frac{1}{2}$ and hence $\Phi(T(v_n)) = v_n(\omega) \ge \frac{1}{2}$ for all $n \in \mathbb{N}$. As $T(v_n) \in \mathrm{BL}(\mathbb{R}, d)$, $n \in \mathbb{N}$, we have shown that $\Phi|\,\mathrm{BL}(\mathbb{R}, d)$ is not σ-smooth. Consequently, $\mathrm{BL}(\mathbb{R}, d)$ does not have the Alexandroff property, too.

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WOLFGANG ADAMSKI
MATHEMATISCHES INSTITUT DER UNIVERSITÄT MÜNCHEN
THERESIENSTR. 39
D–80333 MÜNCHEN
GERMANY

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