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ON THE IDENTITY $L(E,F) = LB(E,F)$ FOR PAIRS OF LOCALLY CONVEX SPACES E AND F

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ABSTRACT. Some new pairs (E,F) of locally convex spaces are given such that every continuous linear mapping from E into F is bounded.

The aim of this note is to study pairs of locally convex spaces (l.c.s.) (E,F) such that every continuous linear mapping from E into F is bounded. We mainly concentrate on the cases when E or F coincide with a countable product ω or a countable direct sum φ of copies of the scalar field $\mathbf{K}$ ($\mathbf{K} = \mathbf{R}$ or $\mathbf{C}$). In these cases complete characterizations are provided. Some of the conditions which occur in our study have been extensively considered in the literature with different purposes (see [**4, 8, 10, 11, 12, 19**]).

We shall use standard notations of locally convex spaces as in [**14** and **15**]. If E is a l.c.s., the set of all continuous seminorms on E will be denoted by $\mathrm{cs}(E)$. If E and F are l.c.s., $L(E,F)$ denotes the linear space of all continuous linear mappings from E into F. A linear mapping $f\colon E \to F$ is said to be *bounded* if there is a 0-neighborhood U in E such that $f(U)$ is bounded in F. We write $LB(E,F)$ for the set of all linear bounded mappings from E into F. Clearly $LB(E,F) \subset L(E,F)$. Following Floret [**12**], a l.c.s. is said to satisfy the *countable neighborhood property* if for every sequence (p_n) in $\mathrm{cs}(E)$ there are $c_n > 0$ and $p \in \mathrm{cs}(E)$ such that $p_n \leq c_n p$, $n \in N$. This condition already appears in [**19**]. Every (gDF)-space has the c.n.p. (see [**14**, Chapter 12]). More information about the c.n.p. can be seen in [**4** and **12**].

A pair (E,F) of l.c.s. is said to satisfy the *localization property* [**5**] if every equicontinuous subset A of $L(E,F)$ is equibounded (i.e., there is a 0-neighborhood U in E such that $\bigcup(f(U)\colon f \in A)$ is bounded in F). Clearly if (E,F) has the localization property, then $L(E,F) = LB(E,F)$. *Each of the following pairs has the localization property* (see [**5**, Proposition 4]):

(a) *E or F is a normed space.*

(b) *E has the c.n.p. and F is metrizable.*

(c) *E is metrizable and F has a countable basis of bounded sets.*

The localization property for pairs of Fréchet spaces was characterized by Vogt in [**21**]. By [**21**, 1.2], if (E,F) is a pair of Fréchet spaces, then $L(E,F) = LB(E,F)$ if and only if (E,F) has the localization property. Defant observed that Vogt's ideas in [**21**] can be used to show that this equivalence remains true if E and F are (DF)-spaces and F is locally complete [**14**]. Applications of the localization property can be seen in [**5, 6, 7, 16, 21,** and **22**].

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A barrelled l.c.s. is said to be *quasi-Baire* [**18**] if it cannot be covered by an increasing seqence of rare subspaces, or, equivalently, if it does not contain a complemented copy of φ (see [**2**]).

PROPOSITION 1. *Let E be a barrelled space and let $F = \operatorname{ind} F_n$ be a strict inductive limit of Banach spaces. The following are equivalent (tfae):*
(1) *(E,F) has the localization property.*
(2) *$L(E,F) = LB(E,F)$.*
(3) *E is quasi-Baire.*

PROOF. (3) $\rightarrow$ (1). Let A be an equicontinuous subset of $L(E,F)$. For each $n \in N$ we set $E_n := \{x \in E | f(x) \in F_n \text{ for each } f \in A\}$. Clearly (E_n) is an increasing sequence of closed subspaces of E. Given $x \in E$, the set $A(x) := \{f(x) | f \in A\}$ is bounded in F, hence there is a certain s with $A(x) \subset F_s$, therefore $x \in E_s$. Since E is quasi-Baire, there is a certain m with $E_m = E$. Thus each $f \in A$ factors through F_m. Since F_m is a Banach subspace of F, the conclusion follows from result (a) in the introduction.

(2) $\rightarrow$ (3). If E is not quasi-Baire, there is a continuous linear mapping g from E onto φ [**2**]. Since F is strict, there is an isomorphism h from φ into F such that $h(\varphi)$ is not included in F_n for each $n \in N$. Define $f\colon E \rightarrow F$ by $f := h \circ g$. Clearly $f \in L(E,F)$ but it is not bounded, a contradiction. □

REMARK 2. (3) $\rightarrow$ (1) above does not depend on the barrelledness of E, but if $E_0 := (\varphi, \sigma(\varphi,\omega))$, then $L(E_0,\varphi) = LB(E_0,\varphi)$ [**8**, 2.12(b)], and E_0 is a countable increasing union of rare subspaces.

A sequence (x_n) in a l.c.s. E is said to be *very strongly convergent* if given any element (c_n) of ω, then $(c_n x_n)$ tends to 0 in E, or equivalently if $(p(x_n)) \in \varphi$ for every $p \in \operatorname{cs}(E)$ (see [**10**, 2.50]). A l.c.s. is said to satisfy the *vanishing sequence property* (v.s.p.) if given any strongly convergent sequence (x_n) there is $m \in N$ such that $x_n = 0$ if $n > m$. This condition already appears in [**19**] in a study of functions whose support is "scalarly compact". Clearly every l.c.s. with a continuous norm and every l.c.s. with the c.n.p. has the v.s.p. A Fréchet space satisfies the v.s.p. if and only if it has a continuous norm (see [**11**]). Applications of l.c.s. with the v.s.p. to infinite dimensional holomorphy can be seen in [**10** and **11**]. A study of l.c.s. with the v.s.p. is included in [**20**].

Following Bellenot and Dubinsky, [**1**], a Fréchet space E is called a *quojection* if for every $p \in \operatorname{cs}(E)$ we have that $E/\ker p$ is normable. These Fréchet spaces are precisely the countable surjective limits of Banach spaces, [**10**, Chapter 6]. They have been considered by several authors (see e.g. [**1**, **9**, **11**, **13**]). Every countable product of Banach spaces is a quojection. Moscatelli, [**17**], gave examples of quojections which are not isomorphic to a product of Banach spaces.

LEMMA 3. *Let E be a nonnormable Fréchet space and let F be a locally complete l.c.s. If $L(E,F) = LB(E,F)$, then F has the v.s.p.*

PROOF. If F does not have the v.s.p., then it contains a subspace G isomorphic to ω by [**20**, Theorem 1] (which also holds for F locally complete). Now it is well known that E has a quotient H isomorphic to ω. Thus, if $Q\colon E \rightarrow H$ is the quotient mapping and $f\colon H \rightarrow G$ is an isomorphism, then $f \circ Q \in L(E,F)$ and it is not bounded, a contradiction. □

The converse of the former lemma is not true, as shown by the identity mapping of a Fréchet space with a continuous norm.

PROPOSITION 4. *Let E be a quojection which is not normable and let F be a locally complete l.c.s. Tfae:*

(1) *(E,F) has the localization property.*

(2) *$L(E,F) = LB(E,F)$.*

(3) *F has the v.s.p.*

(4) *F does not contain a complemented copy of ω.*

PROOF. (1) $\to$ (2) is obvious and (2) $\to$ (3) follows from Lemma 3. (3) and (4) are equivalent according to [**20**, Theorem 1]. It remains to prove that (3) implies (1). Let (q_n) be an increasing fundamental sequence of continuous seminorms on E. Let A be an equicontinuous subset of $L(E,F)$. We claim the existence of $m \in N$ such that $f(x) = 0$ for every $f \in A$ and $x \in E$ with $q_m(x) = 0$. Assume the contrary. We can select a sequence (x_m) in E with $q_m(x_m) = 0$ for each m, and a sequence (f_m) in A such that $f_m(x_m) \neq 0$ for every $m \in N$. Take $p \in \mathrm{cs}(F)$. Since A is equicontinuous, there are $k > 0$ and $s \in N$ such that $p(f(y)) \leq kq_s(y)$ for every $y \in E$ and $f \in A$. Hence, if $m > s$, we have that $0 \leq p(f_m(x_m)) \leq kq_s(x_m) \leq kq_m(x_m) = 0$. Therefore $(f_m(x_m))$ is a nontrivial very strongly convergent sequence in F, contradicting the vanishing sequence property.

Let m be the positive integer determined in the claim. Given $f \in A$ there is a unique continuous linear mapping $\tilde{f}$ from $E/\ker q_m$ into F such that $f = \tilde{f} \circ Q$, $Q\colon E \to E/\ker q_m$ being the canonical surjection. Set $\tilde{A} := \{\tilde{f} | f \in A\}$. Clearly $\tilde{A}$ is an equicontinuous subset of $L(E/\ker q_m, F)$. By assumption $E/\ker q_m$ is normable. We denote by V the closed unit ball of the norm defining the topology of $E/\ker q_m$. Therefore $\bigcup(\tilde{f}(V) | \tilde{f} \in \tilde{A})$ is bounded in F, thus $U := Q^{-1}(V)$ is a 0-neighborhood in E such that $\bigcup(f(U) | f \in A)$ is bounded in F. □

REMARK 5. *For $E = \omega$,* (1)–(4) *of Proposition* 4 *are also equivalent to* (5) *if $f \in L(\omega, F)$, then* $\dim f(\omega)$ *is finite.* Indeed, it is shown in [**20**, Theorem 1] that if $f \in L(\omega,F)$, then either $\dim f(\omega)$ is finite or $f(\omega)$ is isomorphic to ω. Clearly, in the first case f is bounded, while in the second f is not, since the induced mapping $f_0\colon \omega/\ker f \to f(\omega)$ is an isomorphism.

REMARK 6. The local completeness assumption is not needed to prove (3) $\to$ (1) in Proposition 4. In fact, *if E is a quojection and F is a l.c.s. with the v.s.p., then (E,F) has the localization property.* But observe that $F_0 := \varphi$ endowed with the topology induced by ω is a nonlocally complete l.c.s. without v.s.p. but each $f \in L(\omega, F_0)$ is bounded, since its range is finite dimensional [**8**, 2.15(b)].

Proposition 4 is, in some sense, "dual" to Proposition 1. The strong dual of a strict (LB)-space is a quojection and the strong dual of a nonnormable quojection is a strict (LB)-space (see [**9**]). Our next characterization emphasizes the aforementioned "duality" and, in particular, implies that the v.s.p. is a property of the dual pair.

PROPOSITION 7. *Let F be a l.c.s. Tfae:*

(1) *F has the vanishing sequence property.*

(2) *If F' is the increasing union of a sequence (G_n) of subspaces of F', then there is $m \in N$ such that G_m is dense in $(F', \sigma(F',F))$.*

PROOF. (1) $\to$ (2). Suppose that F' is the increasing union of a sequence (G_n) of $\sigma(F',F)$-closed subspaces such that $G_n \neq G_{n+1}$ for each $n \in N$. Take $u_n \in G_{n+1} \backslash G_n$, $n \in N$. By Hahn-Banach's theorem we can select $x_n \in F$ such that $u_n(x_n) = 1$, $u(x_n) = 0$ for each $u \in G_n$, $n \in N$. If $p \in \mathrm{cs}(E)$, the polar set U° of $U := \{x \in E | p(x) \leq 1\}$ is a Banach disc in $(F', \sigma(F',F))$, hence there is $s \in N$ such that $U^\circ \subset G_s$. Therefore $v(x_n) = 0$ for each $v \in U^\circ$ and $n > s$. This implies that $p(x_n) = 0$ if $n > s$. Now, by (1), there is some $m \in N$ with $x_n = 0$ if $n > m$. This contradicts that $u_n(x_n) = 1$ for every $n \in N$.

(2) $\to$ (1). Let (y_n) be a sequence in F such that $(p(y_n)) \in \varphi$ for every $p \in \mathrm{cs}(F)$. For each $n \in N$, let G_n denote the orthogonal in F' of $\{y_n, y_{n+1}, \dots\}$. Clearly (G_n) is an increasing sequence of closed subspaces of $(F', \sigma(F',F))$. Given any $u \in F'$, $(u(y_n)) \in \varphi$, then $u \in G_s$ for a certain s and $F' = \bigcup_{n=1}^{\infty} G_n$. By (2), there is $m \in N$ with $G_m = F'$. This implies $y_n = 0$ if $n > m$. □

Bellenot and Dubinsky, [**1**], introduce the following *condition* $(*)$ on a Fréchet space E: E' is not the union of an increasing sequence of Banach spaces E'_n with E'_n being a closed subspace of E'_{n+1}. They prove that every quojection does not satisfy condition $(*)$. The converse being true if E is reflexive. In our next theorem $\mathcal{NK}$ denotes the class of all nuclear Köthe spaces with a continuous norm.

THEOREM 8. *Let E be a Fréchet space. Tfae*:
(1) *$(E, \lambda(A))$ has the localization property for every $\lambda(A) \in \mathcal{NK}$.*
(2) *$L(E, \lambda(A)) = LB(E, \lambda(A))$ for every $\lambda(A) \in \mathcal{NK}$.*
(3) *$E \otimes_p i\lambda(A)'_b$ is barrelled for every $\lambda(A) \in \mathcal{NK}$.*
(4) *E does not satisfy condition $(*)$ of Bellenot and Dubinsky.*

PROOF. The equivalence of (1), (2) and (3) is a consequence of [**21**, 1.2 and 7.3], and (3) and (4) are equivalent by [**3**, Theorem 2 and Remark below]. □

REMARK 9. The class $\mathcal{NK}$ can be replaced in Theorem 8 by the class of reflexive Fréchet spaces with the bounded approximation property and a continuous norm (compare with our Proposition 15 and Corollary 16).

COROLLARY 10. *Let E be a reflexive Fréchet space. Tfae*:
(1) *(E, F) has the localization property for every l.c.s. F with the v.s.p.*
(2) *$L(E, F) = LB(E, F)$ for every l.c.s. F with the v.s.p.*
(3) *E is a quojection.*

PROOF. (3) $\to$ (1) is a consequence of Remark 6. (2) $\to$ (3) follows from Theorem 8, since E is reflexive. □

A l.c.s. is said to satisfy the *countable boundedness condition* (c.b.c.) if given a sequence (B_n) of bounded subsets of F, there are $c_n > 0$, $n \in N$, such that $\bigcup_{n=1}^{\infty} c_n B_n$ is bounded. A l.c.s. is said to satisfy the *individual countable boundedness condition* (i.c.b.c.) if given any sequence (y_n) in F, there are $c_n > 0$, $n \in N$, such that $(c_n y_n)$ is bounded, or, in other words, if every sequence in F is very weakly convergent, [**10**, 2.51]. Every metrizable space satisfies the c.b.c. These conditions have been used by S. Dierolf [**8**] in a study of the commutability of inductive and projective limits and spaces of continuous linear mappings. She observes [**8**, p. 27], that the subspace of $\mathbf{K}^{\mathbf{R}}$ of all the elements with countably many coordinates distinct from 0, endowed with the topology induced by $\mathbf{K}^{\mathbf{R}}$, has the i.c.b.c. but not the c.b.c. Applications of l.c.s. with the i.c.b.c. to infinite holomorphy can be seen in [**11**].

PROPOSITION 11. *Let F be a l.c.s. Tfae:*
(1) *F satisfies the c.b.c.*
(2) *(φ, F) has the localization property.*

PROOF. (1) $\to$ (2) is a particular case of [**8**, 2.6(a)].

(2) $\to$ (1). Let (B_n) be a sequence of bounded subsets of F. We put $I := \prod_{n=1}^{\infty} B_n$. For each $i \in I$, $i = (i_n)$, $i_n \in B_n$, $n \in N$, we define $f_i \colon \varphi \to F$ by $f_i(a) := \sum_{n=1}^{\infty} a_n i_n$, which is a well-defined continuous linear mapping. Let U be an absolutely convex 0-neighborhood in F. If we show that $V := \bigcap(f_i^{-1})(U)|i \in I)$ is absorbent in φ, then $(f_i|i \in I)$ is an equicontinuous subset of $L(\varphi, F)$. To prove that V is absorbent it is enough to show that each e_m is absorbed by V, e_m being the canonical unit vector in φ. Take $m \in N$. If $i \in I$, $i = (i_n)$, $f_i(e_m) = i_m$, therefore $(f_i(e_m)|i \in I) = B_m$, which is bounded in F, hence there is $b_m > 0$ such that $f_i(e_m) \in b_m U$ for every $i \in I$. Thus $e_m \in b_m V$. Now, $(f_i|i \in I)$ being equicontinuous, we apply (2) to obtain that it is equibounded, hence there is a 0-neighborhood W in φ such that $B := \bigcup(f_i(W)|i \in I)$ is bounded in F. Given $n \in N$, there is $c_n > 0$ with $e_n \in c_n W$. Then $f_i(c_n^{-1} e_n) \in B$ for each $i \in I$, hence $i_n \in c_n B$ for each $i_n \in B_n$. Thus $c_n^{-1} B_n \subset B$ for every $n \in N$ and F satisfies the c.b.c. □

COROLLARY 12. *Let E be a barrelled (DF)-space and F a l.c.s. Consider the following statements:*
(1) *F satisfies the c.b.c.*
(2) *(E, F) has the localization property.*
Then, (a) (1) *always implies* (2), (b) *if E does not contain a total bounded subset, then* (1) *and* (2) *are equivalent.*

PROOF. (a) is a consequence of [**8**, 2.6(a)]. To prove (b) assume that F does not satisfy the c.b.c. By Proposition 11, there is an equicontinuous subset $A \subset L(\varphi, F)$ which is not equibounded. As E does not contain a total bounded subset, there is a continuous linear mapping g from E onto φ [**2**]. Then $A := \{f \circ g | f \in A\}$ is an equicontinuous subset of $L(E, F)$ which is not equibounded, a contradiction. □

PROPOSITION 13. *Let F be a l.c.s. Tfae:*
(1) *F satisfies the i.c.b.c.*
(2) $L(\varphi, F) = LB(\varphi, F)$.

PROOF. It is similar to the one of Proposition 11, but easier. □

A l.c.s. is said to satisfy the *countable linear form property* (*c.l.f.p.*) if given any sequence (u_n) in E', there is a 0-neighborhood U in E such that u_n belongs to the linear span of U° for every $n \in N$. It is easy to see that the c.n.p. implies the c.l.f.p. The converse is false as an analysis of our example [**4**, 1.7] shows.

PROPOSITION 14. *Let E be a l.c.s. Tfae:*
(1) *E has the c.l.f.p.*
(2) $L(E, \omega) = LB(E, \omega)$.

PROPOSITION 15. *Let E be a l.c.s. Tfae:*
(1) *E has the c.n.p.*
(2) *(E, ω) has the localization property.*

PROOF. (1) $\to$ (2) follows from result (b) in the introduction [**5**].

$(2) \to (1)$. Let (U_n) be a sequence of absolutely convex closed 0-neighborhoods in E. We set $B_n := U_n^\circ$ and $I := \prod_{n=1}^\infty B_n$. If $i \in I$, $i = (i_n)$, $i_n \in B_n$, $n \in N$, we define $f_i \colon E \to \omega$ by $f_i(x) := (i_n(x))$, $x \in E$. Clearly $f_i \in L(E, \omega)$ for every $i \in I$. We show that $(f_i | i \in I)$ is an equicontinuous subset of $L(E, \omega)$. If V is a 0-neighborhood in ω, there are $m \in N$ and $c_n > 0$, $n = 1, \ldots, m$, such that $W := \{a \in \omega \mid |a_n| \leq c_n,\ n = 1, \ldots, m\} \subset V$. Clearly $M := \bigcap_{n=1}^m c_n U_n$ is a 0-neighborhood in E and if $x \in M$ and $i = (i_n) \in I$ we have that $f_i(x) = (i_n(x)) \in W$. By (2), $(f_i | i \in I)$ is equibounded, hence there is a closed absolutely convex 0-neighborhood U in E such that $B := \bigcup (f_i(U) | i \in I)$ is bounded in ω. Therefore for each $n \in N$ there is $b_n > 0$ such that $|\pi_n(f_i(x))| \leq b_n$ for every $x \in U$, π_n being the canonical nth projection from ω onto K. Then for each $n \in N$ and $u \in B_n = U_n^\circ$ we get $|u(x)| \leq b_n$ for every $x \in U$, hence $U_n^\circ \subset b_n U^\circ$ and this implies that U_n contains $b_n^{-1} U$. Thus U is contained in $\bigcap_{n=1}^\infty b_n U_n$ and E satisfies the c.n.p. □

COROLLARY 16. *Let E be a l.c.s. and F a Fréchet space which does not have a continuous norm. Tfae:*

(1) *E has the c.n.p.*

(2) *(E, F) has the localization property.*

PROOF. $(1) \to (2)$ is a consequence of result (b) in the introduction [**5**].

$(2) \to (1)$. Assume that E does not satisfy the c.n.p. By Proposition 15, there is an equicontinuous subset A of $L(E, \omega)$ which is not equibounded. Since E does not have a continuous norm, it contains ω as a complemented subspace. Thus we conclude that (E, F) does not have the localization property. □

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