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Our final preliminary comment refers to boundedness of sets. If E is any topological linear space, a subset A of E will be said to be bounded in E if and only if to every neighbourhood U of 0 in E corresponds a number r = r(A, U) > 0 such that $rA = \{rx : x \in A\}$ is contained in U. If E is first countable and d is a semimetric on E defining its topology, boundedness in the above sense of a set $A \subseteq E$ must not be confused with metric boundedness [i.e., with the condition sup $\{d(x, y) : x \in A, y \in A\} < \infty$]. It is in order to minimise the possibility of this confusion that we use the term "first countable" (an abbreviation for "satisfying the first axiom of countability") rather than "semimetrizable".

§ 2. *The construction when* E *is complete and first countable.*

In this section, where E will always denote a complete first countable (locally convex) space and P a set of bounded gauges on E, we will describe the basic construction. Let f^* denote the upper envelope of P.

If the sequence (x_n) figuring in (1.1) and (1.2) is such that $f^*(x_n) = \infty$ for some $n \in N$, no constructional problem remains. So we shall henceforth assume the contrary.

2.1 THEOREM. Suppose that β and α are real numbers satisfying $\beta > \alpha > 0$ and that sequences (x_n) in E, (f_n) in P are such that:

$$f^*(x_n) < \infty \quad \text{for every } n \in N,$$
 (2.1)

$$\lim_{n \to \infty} x_n = 0, \tag{2.2}$$

$$\sup_{n\in\mathbb{N}}f_n(x_n)=\infty. \tag{2.3}$$

Then infinite sequences $n_1 < n_2 < ...$ of positive integers may be constructed such that, for every sequence (γ_n) of real numbers satisfying

$$\alpha \leq \gamma_n \leq \beta \quad \text{for every } n \in N, \tag{2.4}$$

the series

$$\sum_{\nu \in N} \gamma_{\nu} x_{n_{\nu}} \tag{2.5}$$

is normally convergent in E, and

$$f^*(x) \ge \lim_{v \to \infty} f_{n_v}(x) = \infty$$
(2.6)

for each sum x of (2.5).

2.2 CONSTRUCTION AND PROOF. Let (σ_{ν}) be an increasing sequence of continuous seminorms on *E* which define its topology. By initial passage to suitable subsequences, we may and will assume that (2.2) and (2.3) hold in the stronger form:

$$\sum_{n\in\mathbb{N}}\sigma_n(x_n) < \infty, \qquad (2.2')$$

$$\lim_{n \to \infty} f_n(x_n) = \infty. \tag{2.3'}$$

[To do this, define $n_v \in N$ for $v \in N$ by induction in such a way that $n_1 < n_2 < ...,$

$$\sigma_{v}(x_{n_{v}}) \leq 2^{-v} \text{ and } f_{n_{v}}(x_{n_{v}}) > v$$
 (2.7)

for all $v \in N$. This is possible since by (2.2) we can determine $n_1^{\circ} \in N$ such that $\sigma_1(x_n) \leq 2^{-1}$ if $n \geq n_1^{\circ}$, and then, by (2.3) and the fact that each $f \in P$ is finite valued, there exists $n \geq n_1^{\circ}$ such that $f_n(x_n) > 1$; denote the smallest such $n \geq n_1^{\circ}$ by n_1 . When $n_1 < n_2 < \dots n_j$ have been determined so that (2.7) holds for $1 \leq v \leq j$, find (see (2.2)) an integer $n_{j+1}^{\circ} > n_j$ such that $\sigma_{j+1}(x_n) \leq 2^{-j-1}$ if $n \geq n_{j+1}^{\circ}$. Then (2.3) shows that there exists an integer $n \geq n_{j+1}^{\circ}$ such that $f_n(x_n) > j + 1$; put n_{j+1} for the smallest such integer $n \geq n_{j+1}^{\circ}$.

So now we assume (2.1), (2.2') and (2.3') and define one sequence $n_1 < n_2 < ...$ of the required type in the following manner. (Other possibilities are discussed in Remark 2.3 (2) below.) Let n_1 be the smallest $n \in N$ such that

$$f_n(x_n) \geq \beta \alpha^{-1};$$

 n_1 may be determined by (2.3'). Suppose that v is a positive integer and that positive integers $n_1 < n_2 < ... < n_v$ have been defined so that

$$f_{n_j}(x_{n_v}) \leq 2^{-v} \quad \text{whenever} \quad 1 \leq j < v,$$

$$f_{n_v}(x_{n_v}) \geq \beta \alpha^{-1} \sum_{1 \leq j < v} f_{n_v}(x_{n_j}) + \beta \alpha^{-1} v.$$

[An empty sum is defined to be 0; then the conditions are all satisfied when v = 1.] Then (2.2'), (2.3') and the fact that each $f \in P$ is finite-valued imply that there exists an integer $n > n_v$ which satisfies

$$f_{n_j}(x_n) \leq 2^{-\nu - 1} \text{ whenever } 1 \leq j < \nu + 1,$$

$$f_n(x_n) \geq \beta \alpha^{-1} \sum_{1 \leq j < \nu + 1} f_n(x_{n_j}) + \beta \alpha^{-1} (\nu + 1);$$

let n_{v+1} be the smallest such *n*. We then have for each $v \in N$:

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$$f_{n_{i}}(x_{n_{v}}) \leq 2^{-v} \quad \text{whenever} \quad 1 \leq j < v,$$

$$(2.8)$$

$$f_{n_{v}}(x_{n_{v}}) \ge \beta \alpha^{-1} \sum_{1 \le j < v} f_{n_{v}}(x_{n_{j}}) + \beta \alpha^{-1} v.$$
(2.9)

By (2.2') and (2.4), the sum (2.5) is normally convergent in E. Let x be any sum of this series. To establish (2.6), write

 $x = u_{v} + \gamma_{v} x_{n_{v}} + v_{v},$

where $u_v = \sum_{1 \le j < v} \gamma_j x_{n_j}$ and v_v is a sum of the series $\sum_{j > v} \gamma_j x_{n_j}$. Thus $\gamma_v x_{n_v} = x - u_v - v_v$, and so

$$\alpha f_{n_{\nu}}(x_{n_{\nu}}) \leq f_{n_{\nu}}(\gamma_{\nu} x_{n_{\nu}}) \leq f_{n_{\nu}}(x) + f_{n_{\nu}}(u_{\nu}) + f_{n_{\nu}}(v_{\nu}).$$
(2.10)

Now, by (2.4),

$$f_{n_{v}}(u_{v}) \leq \beta \sum_{1 \leq j < v} f_{n_{v}}(x_{n_{j}});$$
(2.11)

and, by (2.4), (2.8) and the fact that each f_n is bounded, hence continuous,

$$f_{n_{v}}(v_{v}) \leq \beta \sum_{j > v} f_{n_{v}}(x_{n_{j}}) \leq \beta \sum_{j > v} 2^{-j} = \beta 2^{-v}.$$
(2.12)

By (2.10), (2.11) and (2.12)

$$\alpha f_{n_{v}}(x_{n_{v}}) \leq f_{n_{v}}(x) + \beta \sum_{1 \leq j < v} f_{n_{v}}(x_{n_{j}}) + \beta 2^{-v},$$

and so, by (2.9),

$$\beta \sum_{1 \le j < \nu} f_{n_{\nu}}(x_{n_{j}}) + \beta \nu \le f_{n_{\nu}}(x) + \beta \sum_{1 \le j < \nu} f_{n_{\nu}}(x_{n_{j}}) + \beta 2^{-\nu}.$$

Hence

$$f_{n_{v}}(x) \geq \beta (v - 2^{-v}),$$

which proves (2.6) and the construction is complete.

2.3 REMARKS. (1) If it is known that

$$D := \{x \in E : f^*(x) < \infty\}$$

is dense in *E*, and if (x_n) and (f_n) satisfy (2.2) and (2.3), we can approximate each x_n so closely by an element y_n of *D* that (2.2) and (2.3) are left intact on replacing x_n by y_n . The hypotheses (2.1)—(2.3) are satisfied when x_n is everywhere replaced by y_n . (2) If it be supposed that (2.2') holds and that sequences (A_n) , $(B_{n,r})$ and (C_n) are known such that $\lim_{n \to \infty} B_{n,r} = 0$ for every $r \in N$, $\lim_{n \to \infty} C_n = \infty$,

$$f^*(x_1) + \dots + f^*(x_n) \leq A_n,$$
$$\max_{1 \leq j \leq r} f_j(x_n) \leq B_{n,r},$$
$$f_n(x_n) \geq C_n,$$

then it is easy to specify a function $\phi_{\alpha,\beta} : N \times N \to N$ in terms of (A_n) , $(B_{n,r})$ and (C_n) such that (2.4) and (2.5) yield (2.6) for every sequence (n_v) such that $C_{n_1} \ge \beta \alpha^{-1}$ and $n_{v+1} \ge \phi_{\alpha,\beta}(n_v, v)$ for every $v \in N$.

(3) Local convexity of E is not essential in 2.1 and 2.2. In the contrary case one may proceed by introducing an invariant semimetric $(x, y) | \rightarrow |x-y|$ defining the topology of E, much as in [2], proof of Theorem 6.1.1, or [15], Chapitre I, § 3, No. 1. Normal summability in E of a series $\sum_{n \in N} z_n$ of elements of E may then be taken to mean the convergence of $\sum_{n \in N} |z_n|$. In place of (2.2') arrange that

$$\sum_{n\in\mathbb{N}}|\beta x_n|<\infty,$$

which will ensure the normal convergence in E of (2.5) whenever (2.4) holds (E being assumed to be complete). The rest of the proof and construction proceeds as before.

This method could, of course, be used when E is locally convex (and first countable and complete); we have not done so because the seminorms σ_n are usually more manageable in practice.

(4) A useful variant of 2.1 may be stated in the following terms.

2.4 Suppose given real numbers $\beta > \alpha > 0$ and sequences (x_n) in E and (f_n) in P such that

$$f^*(x_n) < \infty$$
 for every $n \in N$, (2.1)

$$\{x_n : n \in N\} \text{ is bounded in } E, \qquad (2.2'')$$

$$\sup_{n\in\mathbb{N}}f_n(x_n)=\infty. \tag{2.3}$$

Then one can construct a sequence (λ_n) of real numbers with the following properties:

$$\lambda_n \ge 0, \sum_{n \in \mathbb{N}} \lambda_n < \infty; \qquad (2.13)$$

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for every sequence (γ_n) satisfying (2.4) the series

$$\sum_{n \in N} \gamma_n \lambda_n x_n \tag{2.14}$$

is normally convergent in E; and

$$f^*(x) = \infty \tag{2.15}$$

for every sum x of the series (2.14).

In the sequel we shall denote by $l^1_+(N)$ the set of sequences (λ_n) satisfying (2.13).

PROOF. Define by recurrence a strictly increasing sequence (k_n) of positive integers, taking k_1 to the first $k \in N$ such that $f_k(x_k) > 1^3$ and k_{n+1} to be the first $k \in N$ such that $k > k_n$ and $f_k(x_k) > (n+1)^3$. Then apply 2.1 and 2.2 with x_n and f_n replaced by $n^{-2} x_{k_n}$ and f_{k_n} respectively. This furnishes at least one strictly increasing sequence (n_v) of positive integers such that (2.4) entails that the series

$$\sum_{\nu \in N} \gamma_{\nu} n_{\nu}^{-2} x_{k_{n_{\nu}}}$$
(2.16)

is normally convergent in *E* and that (2.15) holds for every sum *x* of (2.16). It thus suffices to define λ_n to be n_v^{-2} when $n = k_{n_v}$ for some $v \in N$ and to be zero for all other $n \in N$; it is obvious that (2.13) is then satisfied.

§ 3. The construction when E is sequentially complete

3.1 In this section we assume merely that E is a locally convex space which is sequentially complete. Again P will denote a set of bounded gauges on E, and f^* will denote its upper envelope. Suppose given sequences (x_n) in E and (f_n) in P such that (2.1), (2.2'') and (2.3) are satisfied. Then the conclusion of 2.4 remains valid.

PROOF. Consider the continuous linear map T of $l^1(N)$ into E defined by

$$T\xi = \sum_{n\in\mathbb{N}} \xi_n x_n.$$

Evidently, $x_n = T\alpha_n$ for suitably chosen α_n such that $\{\alpha_n : n \in N\}$ is a bounded subset of $l^1(N)$. It therefore suffices to apply 2.4 with *E* replaced by $l^1(N)$, x_n by α_n , and f_n by $f_n \circ T$.

The following corollary will find application in §§ 5 and 6 below.