Added in proof. S. Dineen introduced in his paper *Fonctions analytiques dans les espaces vectoriels topologiques localement convexes* (C. R. Acad. Sci. Paris 274 (1972), A544–A546) the notion of N-projective limits being essentially the basic systems with open projections and studied the polynomial convexity and pseudoconvexity in locally convex spaces with such systems.

Theorem 2.1 holds for every t.v.s. E (not necessarily locally convex).

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On a functional representation of the lattice of projections on a Hilbert space

by

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Abstract. Let $(L, \leqslant, ')$ be a σ-orthocomplemented partially ordered set with a full set of states M. The dual M' of M is defined as the set of functions $\bar{a}\colon M \to [0, 1]$, $a \in L$, where $\bar{a}(m) = m(a)$ for all $m \in M$. It is shown that M' is isomorphic to L, and necessary and sufficient conditions are given in order that a set of functions $M \subset [0, 1]^X$ be the dual of some full set of states on a σ-orthocomplemented poset. If $(L, \leqslant, ')$ is the σ-orthocomplemented lattice of projections on a Hilbert space H and M the set of pure states induced by unit functionals in H^*, $M = \{\psi(u)\colon u \in H^*, \|u\| = 1\}$, then for each $g \in M'$ there is a unique continuous antilinear map $\varphi_g\colon H^* \to H^{**}$ such that $g\psi(u) = \varphi_g(u)(u)$ for all $u \in H^*$, $\|u\| = 1$.

Let $L(H)$ be the set of orthogonal projections on a Hilbert space H. $L(H)$ is an orthomodular lattice with respect to the natural order ($P_1 \leqslant P_2$ if and only if $R(P_1) \subset R(P_2)$ where $R(P)$ denotes the range of P) with the orthogonal complementation $P \to P'$ (where $R(P') = R(P)^{\perp}$). This lattice belongs to a more general class of σ-orthocomplemented partially ordered sets which admit a full set of probability measures. Before we state a theorem about $L(H)$ we shall discuss some properties of this class of partially ordered sets.

Let $(L, \leqslant)$ be a partially ordered set (abbreviated to poset) with a one-to-one map $a \to a'$ of L onto L. $(L, \leqslant, ')$ is said to be a *σ-orthocomplemented poset* provided

(a) $a'' = a$ for all $a \in L$.

(b) $a \leqslant b$ implies $b' \leqslant a'$.

(c) If $a_1, a_2, \ldots$ is a sequence of members of L where $a_i \leqslant a_j'$ for $i \neq j$, then the least upper bound $a_1 \cup a_2 \cup \ldots$ exists in L.

(d) $a \cup a' = b \cup b'$ for all a and b in L. (We denote $a \cup a'$ by 1.)

A σ-orthocomplemented poset is said to be *orthomodular* (see [6]) if

(e) $a \leqslant b$ implies $b = a \cup (b' \cup a)'$.

Let L be a σ-orthocomplemented poset. A map $m\colon L \to [0, 1]$ is said to be a *state on L* if m is a probability measure, i.e. if $m(1) = 1$ and $m(a_1 \cup a_2 \cup \ldots) = m(a_1) + m(a_2) + \ldots$ whenever $a_i \leqslant a_j'$ for $i \neq j$.

If for some $a, b \in L$ we have $a \leqslant b'$, then we say that a is *orthogonal to* b and we write $a \perp b$.

We now assume that L is a σ-orthocomplemented poset and let $m\colon L \to [0,1]$ be a state on L.

A set of states M on L is said to be *full* (see [5]) if $m(a) \leqslant m(b)$ for all $m \in M$ implies $a \leqslant b$. Not every σ-orthocomplemented poset admits a full family of states. It follows e.g. from Theorem 1 that such a poset must necessarily be orthomodular. But this is not a sufficient condition. P. D. Meyer [8] has given examples of orthomodular posets which admit no states at all. As shown by R. J. Greechie [3] there are also orthomodular lattices without states. But on the other hand there are important classes of σ-orthocomplemented posets which do admit full families of states. It follows from Gleason's theorem, to be discussed in the sequel, that the σ-orthocomplemented lattice of projections on a Hilbert space admits in a natural way a full set of states.

Let F be a set of functions from A into B, $F \subset B^A$. Each member a of A gives rise to a function $\bar{a}\colon F \to B$ defined by $\bar{a}(f) = f(a)$ for all $f \in F$. The set of all such functions $F' = \{\bar{a}\colon a \in A\}$ is called the *dual of* F. We have $F' \subset B^F$.

Let L be a σ-orthocomplemented poset with a full set M of states. Thus M is a set of functions from L into $[0,1]$, $M \subset [0,1]^L$. As above, each member $a \in L$ gives rise to a function $\bar{a}\colon M \to [0,1]$ defined by $\bar{a}(m) = m(a)$ for all $m \in M$. Let M' be the set of all such functions, i.e. the dual of M. We have $M' \subset [0,1]^M$. A function in $[0,1]^M$ will be called a *numerical function*. It is easy to see that M' is a σ-orthocomplemented poset with respect to the natural order of real functions ($\bar{a} \leqslant \bar{b}$ if and only if $\bar{a}(x) \leqslant \bar{b}(x)$ for all $x \in M$), with the complementation $\bar{a}' = 1 - \bar{a}$ where 1 denotes the function in M' equal to 1 for all $x \in M$. The correspondence $a \to \bar{a}$ is one-to-one and gives the natural isomorphism between $(L, \leqslant, ')$ and $(M', \leqslant, ')$. In fact, we have $a \leqslant b$ if and only if $m(a) \leqslant m(b)$ for all $m \in M$ (M is full); thus $a \leqslant b$ in L if and only if $\bar{a} \leqslant \bar{b}$ in M'. Hence $a \cup b$ exists in L if and only if $\bar{a} \cup \bar{b}$ exists in M' and $\overline{a \cup b} = \bar{a} \cup \bar{b}$. Moreover, we have $a \cup a' = 1$ and $a \perp a'$ for any $a \in L$; thus $m(a) + m(a') = 1$ for all $m \in M$, and consequently $\bar{a} + \overline{a'} = 1$. Hence $\overline{a'} = 1 - \bar{a} = \bar{a}'$. If $a \perp b$, then $a \leqslant b'$ and consequently $\bar{a} \leqslant \overline{b'} = \bar{b}'$, i.e. $\bar{a} \perp \bar{b}$. If $a = a_1 \cup a_2 \cup \ldots$ with $a_i \perp a_j$ for $i \neq j$, then $m(a) = m(a_1) + m(a_2) + \ldots$ for all $m \in M$ and consequently $\bar{a} = \bar{a}_1 \cup \bar{a}_2 \cup \ldots = \bar{a}_1 + \bar{a}_2 + \ldots$

We see that the representation of L by M' is very convenient because in M' the order is the natural order of real functions, the orthogonal complementation is the subtraction from 1, and the least upper bound of orthogonal members is simply the sum of functions. Moreover, if L is represented by $M' \subset [0,1]^M$, every member m in the domain of the

functions in M', $m \in M$, induces a state $\bar{m}$ on M where $\bar{m}(f) = f(m)$ for all $f \in M$, and the set of all such states is full. Thus we do not have to specify a full set of states on M as we did originally when we started with L.

There arises a converse problem, namely when, for an arbitrary set M, a set L of functions from M into $[0,1]$, $L \subset [0,1]^M$, is a σ-orthocomplemented poset with respect to the natural order of real functions in L with the complementation $f' = 1 - f$. The following theorem gives an answer to this problem.

THEOREM 1. *Let L be a set of functions from a set M into* $[0,1]$ *satisfying the following conditions*:

(i) *The zero function belongs to L.*

(ii) *$f \in L$ implies $1 - f \in L$.*

(iii) *For any sequence $f_1, f_2, \ldots$ of members of L satisfying $f_i + f_j \leqslant 1$ for $i \neq j$ we have $f_1 + f_2 + \ldots \in L$.*

Then L is a σ-orthomodular poset with respect to the natural order of real functions in $[0,1]^M$ with the complementation $f' = 1 - f$. If $f \leqslant g'$, $f, g \in L$, then $f \cup g = f + g$. Each $m \in M$ induces a state $\bar{m}$ on L where $\bar{m}(f) = f(m)$ for all $f \in L$, and the family of states $\bar{M} = \{\bar{m}\colon m \in M\}$ is full.

Conversely, if L is a σ-orthocomplemented poset with a full set M of states, then the dual M' of M satisfies conditions (i)–(iii) *and consequently L is isomorphic to M' and is orthomodular.*

Proof. Assume that $L \subset [0,1]^M$ satisfies conditions (i)–(iii). We must show that $(L, \leqslant, ')$ satisfies conditions (a)–(e) of the definition of a σ-orthomodular poset. Conditions (a) and (b) are evidently satisfied. We shall prove (c). Observe first that taking in (iii) $f_{n+1} = f_{n+2} = \ldots = 0$ we see that for any finite sequence $f_1, f_2, \ldots, f_n$ satisfying $f_i + f_j \leqslant 1$ for $i \neq j$ we have $f_1 + f_2 + \ldots + f_n \in L$. We have in L $f_1 \leqslant f_2'$ equivalent to $f_1 + f_2 \leqslant 1$. We first prove that, for $f_1 \leqslant f_2'$, $f_1 \cup f_2$ exists and $f_1 \cup f_2 = f_1 + f_2$. We have $f = f_1 + f_2 \in L$. Let, for $g \in L$, $f_1 \leqslant g$ and $f_2 \leqslant g$. This means that $f_1 + g' \leqslant 1$ and $f_2 + g' \leqslant 1$. Hence the sequence $f_1, f_2, g', 0, \ldots$ satisfies the assumption in (iii) and consequently $f_1 + f_2 + g' \in L$, which implies $f_1 + f_2 + g' \leqslant 1$, i.e. $f_1 + f_2 \leqslant g$. Thus $f \leqslant g$, which implies that $f_1 \cup f_2 = f$. We now proceed by induction. Assume that, for all sequences $f_1, f_2, \ldots, f_n$ of length n, $f_i \in L$, satisfying $f_i + f_j \leqslant 1$ for $i \neq j$, the least upper bound $f_1 \cup f_2 \cup \ldots \cup f_n$ exists and $f_1 \cup f_2 \cup \ldots \cup f_n = f_1 + f_2 + \ldots + f_n$. Let $f_1, f_2, \ldots, f_n, f_{n+1}$ be any sequence of members of L where $f_i + f_j \leqslant 1$ for $i \neq j$. By (iii) we infer that $f_1 + f_2 + \ldots + f_{n+1} \in L$. By the induction hypothesis, $f = f_1 + f_2 + \ldots + f_n = f_1 \cup f_2 \cup \ldots \cup f_n$. Consequently $f + f_{n+1} \leqslant 1$. By the part just proved, $f \cup f_{n+1} = f + f_{n+1}$. Hence $f_1 \cup f_2 \cup \ldots \cup f_{n+1} = f_1 + f_2 + \ldots + f_{n+1}$. Now let $f_1, f_2, \ldots$ be a sequence where $f_i + f_j \leqslant 1$ for $i \neq j$. By (iii) we have $f = f_1 + f_2 + \ldots \in L$. We must show that $f = f_1 \cup f_2 \cup \ldots$ Let $f_i \leqslant g$, $i = 1, 2, \ldots$ Then $f_1 \cup f_2 \cup \ldots \cup f_n$ exists for $n = 1, 2, \ldots$, and

$f_1 \cup f_2 \cup \ldots \cup f_n = f_1 + f_2 + \ldots + f_n \leqslant g$. Consequently $\sum_{i=1}^{n} f_i \leqslant g$ for $n = 1, 2, \ldots$ Hence $\sum_{i=1}^{\infty} f_i \leqslant g$, i.e. $f \leqslant g$. This shows that $f = f_1 \cup f_2 \cup \ldots$ exists and $f = f_1 + f_2 + \ldots$ Hence (c) holds. For any $f \in L$ we have $f + (1-f) \leqslant 1$, i.e. f and f' are orthogonal. By the already proved part of the theorem $f \cup f'$ exists in L and $f \cup f' = f + f' = f + (1-f) = 1$. So (d) holds. To show that (e) also holds, let $f \leqslant g$, $f, g \in L$. This implies that $g' + f \leqslant 1$ and $g' \cup f = g' + f = (1-g) + f$. Consequently, $h = (g' \cup f) = 1 - (1 - g + f) = g - f \in L$. Hence $f + h = g \leqslant 1$. Hence $f \cup h = f + h$. We see that $f \cup (g' \cup f)' = f + (g - f) = g$, which means that (e) holds. Hence the first part of the theorem has been proved. The remainder of the theorem follows from the discussion preceeding the theorem.

For some applications in quantum mechanics, it is important to decide when a σ-orthocomplemented poset with a full family of states (or a subset of it) is a Boolean σ-algebra. Using the representation of L by M' we easily get the following criterion.

THEOREM 2. *Let $L \subset [0,1]^M$ be a set of functions from a set M into $[0,1]$ satisfying conditions* (i)–(iii) *of Theorem* 1. *Then L is a Boolean σ-algebra (with respect to the natural order of real functions with the complementation $f' = 1 - f$) if and only if the following condition holds:*

(iv) *For any $f, g \in L$ there are $h_1, h_2, h_3 \in L$, $h_i + h_j \leqslant 1$ for $i \neq j$, such that $f = h_1 + h_2$, $g = h_2 + h_3$.*

Proof. By Theorem 1, L is a σ-orthomodular poset. We shall show that L is a lattice. For $f, g \in L$, we have $f = h_1 + h_2$, $g = h_2 + h_3$, where $h_i + h_j \leqslant 1$ for $i \neq j$. Consequently, by Theorem 1, $f = h_1 \cup h_2$, $g = h_2 \cup h_3$ and $h_1 + h_2 + h_3 \in L$. Hence $h_1 + h_2 + h_3 = h_1 \cup h_2 \cup h_3 = (h_1 \cup h_2) \cup (h_2 \cup h_3) = f \cup g$ and the join of any two elements exists. Since $f \cap g = (f' \cup g')'$, the meet of any two elements exists. Hence L is a σ-orthomodular lattice. It is known that an orthocomplemented lattice is distributive if and only if for any $f, g \in L$ there are $h_1, h_2, h_3 \in L$, $h_i \perp h_j$ for $i \neq j$, such that $f = h_1 \cup h_2$, $g = h_2 \cup h_3$ (this fact is due to Fullis [1]). Hence L is a σ-orthomodular distributive lattice, i.e. a Boolean σ-algebra. The only if part of the theorem is evident. For a more detailed discussion of numerical representation of Boolean algebras see [7].

We shall now investigate the case where $L = L(H)$ is the orthomodular lattice of (orthogonal) projections on a Hilbert space H. A state $m: L(H) \to [0,1]$ on $L(H)$ is said to be pure if $m = cm_1 + (1-c)m_2$, $0 < c < 1$, for any states m_1, m_2 on $L(H)$ implies $m = m_1 = m_2$. Let M be the set of all pure states on $L(H)$. If $u \in H$ is a unit vector $\|u\| = 1$, then $m(P) = (Pu, u)$, $P \in L(H)$, defines a pure state on $L(H)$. A. M. Gleason has shown in [2] that every pure state on $L(H)$ arises in the above way; that is, there is a unique map ψ from the unit sphere $S = \{u \in H: \|u\| = 1\}$ onto M, $\psi: S \to M$, such that $\psi(u)(P) = (Pu, u)$ for all $u \in S$, $P \in L(H)$. We call ψ the Gleason map. The map ψ is not one-to-one since u and cu, $|c| = 1$, induce the same state. Gleason's theorem implies that M is a full set of states on $L(H)$. In fact, $m(P_1) \leqslant m(P_2)$ for all $m \in M$ implies $(P_1 u, u) \leqslant (P_2 u, u)$ for all $u \in S$; that is, $((P_2 - P_1)u, u) \geqslant 0$ for all $u \in H$, $\|u\| = 1$, which means that $P_1 \leqslant P_2$.

Since M is a full set of states on $L(H)$, Theorem 1 applies and we can form the dual M' of M. We thus have a triple $(L(H), M, M')$ which is reflexive in the sense that M' is isomorphic to $L(H)$. We have a similar situation when we consider the Hilbert space H, the conjugate space H^* and the second conjugate space H^{**}. As a Hilbert space is reflexive, we have $H^{**} = H$. Formally, H^* is the set of all continuous linear functionals on H, i.e. $H^* \subset C^H$, and by the reflexivity of H, H^{**} is the dual of H^*, $H^{**} = (H^*)'$. So we have again a triple $(H, H^*, (H^*)')$, where $(H^*)' = H^{**} \cong H$. Since by Riesz's theorem every functional $u \in H^*$ arises from a unique vector $\bar{u} \in H$ where $u(x) = (x, \bar{u})$ for all $x \in H$, and the map $u \to \bar{u}$ is norm-preserving, we see that there is a unique map $\psi: S \to M$ from the unit sphere of H^* onto M such that $\psi(u)(P) = (P\bar{u}, \bar{u})$ for all $u \in S$ and $P \in L(H)$. We again call ψ the Gleason map. We see that we have a natural map ψ from the unit sphere of H^* onto M. We may ask whether it is possible to obtain the numerical functions in $M' \subset [0,1]^M$ from functions in $(H^*)' = H^{**} \subset C^{H^*}$. We shall show that this can be accomplished by applying some "selecting functions" to the functions in H^{**}. Namely, if we have a set F of functions from A into B, $F \subset B^A$, we can form a new function f from A into B by applying any function $\varphi: A \to F$, where f is defined by $f(u) = \varphi(u)(u)$ for all $u \in A$. Thus for any u from the domain A we obtain the value $f(u)$ by selecting first a function $\varphi(u)$ from the set F and then calculating the value of $\varphi(u)$ at the point u. This motivates calling φ a *selecting function*. We shall show that the functions in M' are obtainable from functions in H^{**} by way of the above procedure. We have the following theorem.

THEOREM 3. *Let H be a Hilbert space and let $L(H)$ be the σ-orthocomplemented lattice of projections on H. Let M be the set of all pure states on $L(H)$ and let M' be the dual of M. Let $\psi: S \to M$ be the Gleason map from the unit sphere of H^* onto M. For each $g \in M'$ there is a unique continuous antilinear map $\varphi_g: H^* \to H^{**}$ such that $g\psi(u) = \varphi_g(u)(u)$ for all $u \in S$.*

Proof. For each $g \in M'$ we define a map $\varphi_g: H^* \to H^{**}$ as follows. Since $M' \cong L(H)$, there is a unique projection $P_g \in L$ such that $m(P_g) = g(m)$ for all $m \in M$. By Riesz's theorem for every $u \in H^*$ there is a unique $\bar{u} \in H$ such that $u(x) = (x, \bar{u})$ for all $x \in H$. Then $P_g \bar{u} \in H$ gives rise to a functional $j(P_g \bar{u}) \in H^{**}$, where $j: H \to H^{**}$ denotes the natural isomorphism of H onto H^{**} satisfying $j(x)(f) = f(x)$ for all $f \in H^*$ and $x \in H$. We now define a map φ_g by $\varphi_g(u) = j(P_g \bar{u})$ for all $u \in H^*$. This is a map from H^* into H^{**}. Since $u \mapsto \bar{u}$ is continuous antilinear, P_g and j are continuous linear, we infer that φ_g is continuous antilinear. We now show that $g\psi(u) = \varphi_g(u)(u)$ for all $u \in S$, where $S = \{u \in H^*: \|u\| = 1\}$. We have $g\psi(u) = \psi(u)(P_g) = (P_g\bar{u}, \bar{u})$ by the definition of ψ, and $\varphi_g(u)(u) = j(P_g\bar{u})(u) = u(P_g\bar{u}) = (P_g\bar{u}, \bar{u})$. Hence $g\psi(u) = \varphi_g(u)(u)$ for all $u \in S$. We now show that φ_g is uniquely determined. Let φ_g' be a continuous antilinear map of H^* into H^{**} such that $\varphi_g'(u)(u) = \varphi_g(u)(u)$ for all $u \in S$. We have to show that $\varphi_g'(u) = \varphi_g(u)$ for all $u \in H^*$. Since φ_g is a continuous antilinear map of H^* into H^{**}, $\varphi_g(u)(w)$ is a Hermitian form on H^* (linear in w and antilinear in u). Hence there is a continuous linear operator $A: H^* \to H^*$ such that $\varphi_g(u)(w) = (Aw, u)$ for all $u, w \in H^*$. Similarly we have $\varphi_g'(u)(w) = (A'w, u)$. By assumption we have $(Au, u) = (A'u, u)$ for all $u \in S$. Hence two quadratic forms coincide on the unit sphere. This implies (see e.g. [4]) that $A = A'$ and consequently $\varphi_g(u)(w) = \varphi_g'(u)(w)$ for all $u, w \in H^*$. Hence $\varphi_g(u) = \varphi_g'(u)$ for all $u \in H$. Hence $\varphi_g = \varphi_g'$ and φ_g is uniquely determined. This concludes the proof of the theorem.

We see from Theorem 3 that by applying the selecting functions φ_g, $g \in M'$, to functions in H^{**} we obtain the set of numerical functions $\{g\psi: g \in M'\} \subset [0, 1]^S$. Although this is not the original set M', it is easy to see that $\{g\psi: g \in M'\}$ is a σ-orthomodular poset with respect to the natural order of real functions with the complementation $f' = 1-f$ which is isomorphic to M'. In fact, since ψ is onto M, $g_1\psi \leqslant g_2\psi$ is equivalent to $g_1 \leqslant g_2$ and $1-g\psi = (1-g)\psi$. Hence the set $\{g\psi: g \in M'\}$ also forms a representation of $L(H)$ by a set of numerical functions satisfying the conditions of Theorem 2. Consequently we can state the following corollary.

COROLLARY. *The σ-orthomodular lattice of projections on a Hilbert space H can be isomorphically represented by a lattice of numerical (real) functions, where all the functions can be obtained from functions in H^{**} by applying to them suitable continuous antilinear selecting functions.*

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