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SPECTRAL SPACES OF COUNTABLE ABELIAN LATTICE-ORDERED GROUPS

FRIEDRICH WEHRUNG

ABSTRACT. A compact topological space X is *spectral* if it is sober and the compact open subsets of X form a basis of the topology of X , closed under finite intersections. It is well known that the spectrum of an Abelian ℓ -group with unit — equivalently, of an MV-algebra — is spectral.

Theorem. *A topological space X is isomorphic to the spectrum of some countable Abelian ℓ -group with unit (resp., MV-algebra) iff X is spectral, has a countable basis of open sets, and for any points x and y in the closure of a singleton $\{z\}$, either x is in the closure of $\{y\}$ or y is in the closure of $\{x\}$.*

We establish this result by proving that a countable distributive lattice D with zero is isomorphic to the lattice of all principal ideals of an Abelian ℓ -group (we say that D is ℓ -representable) iff for all $a, b \in D$ there are $x, y \in D$ such that $a \vee b = a \vee y = b \vee x$ and $x \wedge y = 0$. On the other hand, we construct a non- ℓ -representable bounded distributive lattice, of cardinality \aleph_1 , with an ℓ -representable countable elementary sublattice. In particular, there is no first-order characterization, of ℓ -representable distributive lattices, in arbitrary cardinality.

1. INTRODUCTION

1.1. Statement of the problem. A *lattice-ordered group*, or ℓ -group for short, is a group G endowed with a translation-invariant lattice ordering. An ℓ -ideal of G is a convex, normal ℓ -subgroup I of G . We say that I is *prime* if $x \wedge y \in I$ implies that either $x \in I$ or $y \in I$, for all $x, y \in G$. We define the ℓ -spectrum of G as the set $\text{Spec}_\ell G$ of all prime ℓ -ideals of G , endowed with the topology whose closed sets are exactly the sets $V_X \stackrel{\text{def}}{=} \{P \in \text{Spec}_\ell G \mid X \subseteq P\}$, for $X \subseteq G$. Characterizing the spaces $\text{Spec}_\ell G$, for Abelian ℓ -groups G , is a long-standing open problem. Although the work on that problem started more than twenty years ago, the first printed occurrence of its statement that we are aware of is Mundici [34, Problem 2], where it is stated in an equivalent form:

“Which topological spaces are homeomorphic to $\text{Spec}(A)$ for some MV-algebra A ?”

To explain the connection, the concept of *MV-algebra* is tailored to describe, by a finite set of identities, the structure of any interval of the form $[0, u]$ in an

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Abelian ℓ -group G , in terms of the binary operation $(x, y) \mapsto (x + y) \wedge u$ and the unary operation $x \mapsto u - x$. There are natural concepts of ideal, then prime ideal, and thus also of spectrum (we will say *MV-spectrum*), in any MV-algebra, similar to those defined for Abelian ℓ -groups. In [33], Mundici constructs a category equivalence between the category of all Abelian ℓ -groups with unit, with unit-preserving ℓ -homomorphisms, and the variety (in the universal algebraic sense) of all MV-algebras (see also Marra and Mundici [29, 30]). Under that equivalence, the various concepts of ideal, prime ideal, and spectrum correspond, so the question about Abelian ℓ -groups with order-unit is equivalent to the one about MV-algebras.

1.2. Completely normal spectral spaces. The constructions, of the spectrum of an Abelian ℓ -group and the spectrum of an MV-algebra, are both particular cases of the following one. The spectrum of a distributive lattice D with zero can be defined in a similar way as the ℓ -spectrum of an Abelian ℓ -group. A lower subset I , in a distributive lattice D with zero, is an *ideal* if it is closed under finite joins (in particular, $0 \in I$). Further, we say that I is *prime* if $x \wedge y \in I$ implies that either $x \in I$ or $y \in I$, for all $x, y \in D$. This enables us to define the spectrum of D , and it is well known, since Stone [39], that spectra of bounded distributive lattices are exactly the so-called *spectral spaces* (cf. Definition 4.1). They are also the same as spectra of commutative, unital rings (cf. Hochster [24]). Moreover, it turns out that the ℓ -spectrum of an Abelian ℓ -group G is homeomorphic to the spectrum of the lattice $\text{Id}_c G$ of all principal ℓ -ideals of G (see Section 4 for details).

Does every spectral space appear as the ℓ -spectrum of an Abelian ℓ -group? The answer has been known for a long time to be negative, and can be conveniently stated in terms of the *specialization order*. In any topological space X , let $x \leq y$ hold if y belongs to the closure of x , for all $x, y \in X$. The binary relation \leq is a preorder on X , called the *specialization (pre)order on X* . It is antisymmetric iff X is T_0 , which holds, in particular, if X is spectral.

A spectral space X is *completely normal*¹ if every principal filter of X is a chain, for every $p \in X$ (cf. Definition 4.3); that is, the specialization order is a *root system*. Not every spectral space is completely normal, but the ℓ -spectrum of any Abelian ℓ -group is completely normal. And then it turns out that completely normal spectral spaces also appear in the different context of *real spectra*: *The real spectrum of any commutative, unital ring is a completely normal spectral space* (cf. Coste and Roy [12], Dickmann [16]).

If we let go of the topology for a while, Cignoli and Torrens [11] characterized all posets (i.e., partially ordered sets) isomorphic to the specialization order on the MV-spectrum of some MV-algebra. An analogue result is proved in Dickmann, Gluschankof, and Lucas [17] about real spectra. It is noteworthy that both results represent the same class of root systems, called *spectral root systems*.

Is every completely normal spectral space an ℓ -spectrum? Delzell and Madden [14, Theorem 2] construct a completely normal spectral space, whose specialization order is a root system, which is not isomorphic to any MV-spectrum. However, that example is not *second countable* (i.e., its topology has no countable basis of open sets). The spectral space from Example 5.5, in the present paper, is similar, although not homeomorphic.

¹In some references, a topological space X is completely normal if every subspace of X is normal. This definition is (strictly) stronger than ours, see Example 4.5.

How about the countable case? Trying to represent a second countable, completely normal spectral space X , a basic idea would be to express X as an inverse limit, for a suitable concept of morphism, of finite completely normal spectral spaces, then lift the arrows between individual building blocks, and then construct a direct limit (of Abelian ℓ -groups). Finite completely normal spectral spaces arise from finite root systems, and it has been known for a long time that those can be lifted by lexicographical powers of, say, the integers (see, for example, Bigard, Keimel, and Wolfenstein [5, Section 5.4]). However, such a plan would rely on the hope that our spectral space X be *profinite*. And Di Nola and Grigolia [15] found an example showing that this is not always the case; so we need to look elsewhere.

In a different direction, Iberkleid, Martínez, and McGovern proved in [26, Theorem 3.1.1] that *Every completely normal distributive lattice D with zero, such that for all $a, b \in D$ there exists a smallest $x \in D$ with $a \leq b \vee x$, is ℓ -representable.*

1.3. Reduction to a problem about distributive lattices. Any spectral space is determined, up to homeomorphism, by its (distributive) lattice of compact open subsets, and every distributive lattice with zero appears that way (Stone [39]; see Proposition 4.2). It follows that the problem, of characterizing ℓ -spectra of Abelian ℓ -groups, is equivalent to characterizing the distributive lattices with zero isomorphic to $\text{Id}_c G$ for some Abelian ℓ -group G (cf. Lemma 4.7) — we shall call such lattices *ℓ -representable*. It follows that the question, of characterizing *second countable ℓ -spectra*, is equivalent to the following one:

Which countable distributive lattices are ℓ -representable?

Every ℓ -representable distributive lattice D satisfies a lattice-theoretical version of complete normality, which is equivalent to saying that for all $a, b \in D$ there are $x, y \in D$ such that $a \vee b = a \vee y = x \vee b$ and $x \wedge y = 0$ (Definition 4.3), and also to saying that the spectrum (of our distributive lattice) is completely normal (cf. Proposition 4.4). Completely normal lattices are studied in depth (under the name “relatively normal lattices”) in Snodgrass and Tsinakis [37, 38]. Delzell and Madden’s aforementioned example shows that there are uncountable, non- ℓ -representable completely normal bounded distributive lattices.

Our main result is the following:

Theorem 11.1. *Every countable, completely normal distributive lattice with zero is ℓ -representable.*

As immediate corollaries of Theorem 11.1, we mention the following:

- (1) (Corollary 11.2) *A second countable spectral space is an ℓ -spectrum iff it is completely normal;*
- (2) (Corollary 11.3) *For any countable ℓ -group G , there is a countable Abelian ℓ -group A such that the lattices of convex ℓ -subgroups of G and A are isomorphic;*
- (3) (Corollary 11.4) *Every second countable real spectrum is homeomorphic to some ℓ -spectrum.*

1.4. Overview of the paper. In **Section 2**, we review the basic facts required in the proof of Theorem 11.1, mostly about distributive lattices, Heyting algebras, and topological vector spaces. In **Section 3**, we do the same for Abelian ℓ -groups, in particular recalling the classical description of free Abelian ℓ -groups and their ℓ -ideals, arising from the Baker-Beynon duality. In **Section 4** we present an overview

of (generalized) spectral spaces. This enables us to reduce our problems, on ℓ -spectra, to problems on distributive lattices with zero (Lemma 4.7).

Section 5 contains a few non- ℓ -representability results, mainly

- (1) (Proposition 5.3) *The class of all ℓ -representable distributive lattices is not closed under infinite products;*
- (2) (Example 5.5) *There is a non- ℓ -representable bounded distributive lattice \mathbf{D}_{ω_1} , of cardinality \aleph_1 , with an ℓ -representable countable elementary sublattice \mathbf{D}_ω .*

Section 6 introduces the crucial lattice-theoretical concepts of *consonence*, defined as a local version of complete normality, and of a *difference operation*. The latter concept, inspired by the dimension monoid construct of Wehrung [40], is designed to approximate the above-mentioned property, not valid in all completely normal distributive lattices, that for all a, b there is a smallest x such that $a \leq b \vee x$.

Section 7 introduces the main lattice-theoretical extension results required in our proof of Theorem 11.1, most notably the rather technical Lemma 7.3. Those extension results can be roughly described as follows. We are given a finite distributive lattice E , a bounded sublattice — in fact a Heyting subalgebra — D of E , a completely normal distributive lattice L with zero, and a 0-lattice homomorphism $f: D \rightarrow L$. We find convenient sufficient conditions for the existence of an extension of f to a homomorphism from E to L . In Lemma 7.3, those conditions are stated in terms of consonence of f and the join-irreducible elements of D .

Section 8 introduces the finite distributive lattices coming in replacement for the missing “completely normal finite building blocks” whose non-existence is proved in Di Nola and Grigolia [15] (cf. Section 1.2). Our building blocks, typically denoted by $\text{Op}(\mathcal{H})$, are generated by the open half-spaces associated with finitely many closed hyperplanes in a topological vector space \mathbb{E} . They are finite Heyting subalgebras of the lattice of all open subsets of \mathbb{E} . They are not, in general, completely normal.

The join-irreducible members of $\text{Op}(\mathcal{H})$ are further investigated in **Section 9**. An important observation is that *Every join-irreducible member P of $\text{Op}(\mathcal{H})$ is convex, and if P_* denotes the lower cover of P , then $P \setminus P_*$ is convex.* This enables us to reach, in Lemma 9.4, a specialization, to lattices of the form $\text{Op}(\mathcal{H})$, of the homomorphism extension property established in Lemma 7.3. Further homomorphism extension lemmas, on lattices $\text{Op}(\mathcal{H})$, are deduced in **Section 10**.

All those results are put together in **Section 11**, where we state our main theorem (Theorem 11.1) and a few corollaries. In **Section 12**, we discuss a few related results and open problems.

2. BASIC CONCEPTS, NOTATION, TERMINOLOGY

2.1. General. We set $[n] \stackrel{\text{def}}{=} \{1, 2, \dots, n\}$, for every natural number n . Also, $\omega = \{0, 1, 2, \dots\}$ is the first limit ordinal, and ω_1 is the first uncountable ordinal.

Throughout the paper, “countable” means “at most countable”.

In any commutative monoid, let $x \leq y$ hold if there is z such that $x + y = y$, and let $x \propto y$ hold if $x \leq ny$ for some positive integer n . We set $G^+ \stackrel{\text{def}}{=} \{x \in G \mid 0 \leq x\}$, for every partially ordered group G (denoted additively).

2.2. Posets and lattices. A standard reference for lattice theory is Grätzer [22]. For any subsets X and Y in a poset P , we set

$$\begin{aligned} X \downarrow Y &\stackrel{\text{def}}{=} \{x \in X \mid (\exists y \in Y)(x \leq y)\}, \\ X \uparrow Y &\stackrel{\text{def}}{=} \{x \in X \mid (\exists y \in Y)(x \geq y)\}, \end{aligned}$$

and we write $X \downarrow a$, $X \uparrow a$ instead of $X \downarrow \{a\}$, $X \uparrow \{a\}$, respectively, if there is no ambiguity on the ambient poset. We also write $\downarrow X$ and $\uparrow X$ instead of $P \downarrow X$ and $P \uparrow X$, respectively, if there is no ambiguity on P . We say that X is

- a *lower subset* (resp., *upper subset*) of P if $X = \downarrow X$ (resp., $X = \uparrow X$);
- a *cointial* subset of P if $P = \uparrow X$.

For posets P and Q , a map $f: P \rightarrow Q$ is *isotone* (resp., *antitone*) if $x \leq y$ implies that $f(x) \leq f(y)$ (resp., $f(y) \leq f(x)$), for all $x, y \in P$.

A poset P is a *root system* if $P \uparrow p$ is a chain for every $p \in P$; that is, for all $p, x, y \in P$, if $p \leq x$ and $p \leq y$, then either $x \leq y$ or $y \leq x$.

For any maps f and g from a set X to a poset P , we set

$$\llbracket f \leq g \rrbracket \stackrel{\text{def}}{=} \{x \in X \mid f(x) \leq g(x)\},$$

and we define similarly $\llbracket f \geq g \rrbracket$, $\llbracket f = g \rrbracket$, $\llbracket f < g \rrbracket$, $\llbracket f > g \rrbracket$, $\llbracket f \neq g \rrbracket$.

We will often denote by 0 (resp., 1) the smallest (resp., largest) element in a lattice L . For lattices K and L with zero (i.e., least element), a lattice homomorphism $f: K \rightarrow L$ is a *0-lattice homomorphism* if $f(0_K) = 0_L$. We define similarly 1-lattice homomorphisms and 0, 1-lattice homomorphisms. We denote by $\text{Ji } L$ (resp., $\text{Mi } L$) the set of all join-irreducible (resp., meet-irreducible) elements in L .

Lemma 2.1 (folklore). *Let D be a finite distributive lattice. Then every join-irreducible element p of D is join-prime, that is, it is nonzero and $p \leq x \vee y$ implies that $p \leq x$ or $p \leq y$, for all $x, y \in D$. Moreover, the subset $\{x \in D \mid p \not\leq x\}$ has a largest element p^\dagger . The assignment $p \mapsto p^\dagger$ defines an order-isomorphism from $\text{Ji } D$ onto $\text{Mi } D$.*

We say that a (necessarily distributive) lattice D is a *Heyting algebra* (cf. Johnstone [27]) if for all $a, b \in D$, there is a largest $x \in D$ such that $a \wedge x \leq b$, then denoted by $a \rightarrow b$ (or $a \rightarrow_D b$ if D needs to be specified) and called the *Heyting residue* of a by b . The operation \rightarrow is then called the *Heyting implication* on D .

For a distributive lattice D , we set

$$a \ominus b \stackrel{\text{def}}{=} \{x \in D \mid a \leq b \vee x\}, \quad \text{for all } a, b \in D. \quad (2.1)$$

Hence, D is a *dual Heyting algebra* iff $a \ominus b$ has a smallest element, whenever $a, b \in D$. We say that D has *countably based differences* if $a \ominus b$ has a countable cointial subset, whenever $a, b \in D$.

A lattice L is *complete* if every subset of L has a join (equivalently, every subset of L has a meet). An element a of L is *compact* if for every $X \subseteq L$, if $a \leq \bigvee X$, then $a \leq \bigvee Y$ for some finite subset Y of X . A complete lattice L is *algebraic* if every element of L is a join of compact elements. A lattice is algebraic iff it is isomorphic to the ideal lattice of its $(\vee, 0)$ -semilattice of compact elements.

2.3. Topological spaces, vector spaces. For a topological space X , we denote by $\text{int}(Z)$ (resp., $\text{cl}(Z)$) the interior (resp., the closure) of any subset Z of X . The lattice $\mathcal{O}(X)$ of all open subsets of X is a complete Heyting algebra (cf. Section 2.2), with Heyting implication given by

$$(U \rightarrow V) = \text{int}((\mathbb{C}U) \cup V), \quad \text{for all } U, V \in \mathcal{O}(X).$$

For any subset X in a real vector space \mathbb{E} , we denote by $\text{conv}(X)$ the convex hull of X , and by $\text{cone}(X)$ the convex cone generated by X ; so $\text{cone}(X) = \mathbb{R}^+ \cdot \text{conv}(X)$.

The following is a well known consequence of the Hahn-Banach Theorem, usually known as Farkas' Lemma (see, for example, De Loera, Hemmecke, and Köppe [13, Section 1.2]). While this lemma is usually stated in the finite-dimensional case, the general case can easily be reduced to the finite-dimensional one by working in \mathbb{E}/F , where $F \stackrel{\text{def}}{=} \ker(c) \cap \bigcap_{i=1}^n \ker(b_i)$.

Lemma 2.2. *Let \mathbb{E} be a real vector space, let n be a nonnegative integer, and let b_1, \dots, b_n, c be linear functionals on \mathbb{E} . Then $\bigcap_{i=1}^n \llbracket b_i \geq 0 \rrbracket \subseteq \llbracket c \geq 0 \rrbracket$ iff $c \in \text{cone}(\{b_1, \dots, b_n\})$.*

We also record two elementary lemmas, which will be useful in the sequel.

Lemma 2.3. *Let A and F be convex subsets in a real topological vector space \mathbb{E} , with F closed and $F \cap \text{int}(A) \neq \emptyset$. Then $\text{cl}(F \cap A) = F \cap \text{cl}(A)$.*

Proof. Fix $u \in F \cap \text{int}(A)$, and let $p \in F \cap \text{cl}(A)$. Since F is convex, $(1-\lambda)p + \lambda u \in F$ for each $\lambda \in [0, 1]$. Moreover, since $u \in \text{int}(A)$, $p \in \text{cl}(A)$, and A is convex, $(1-\lambda)p + \lambda u$ belongs to A , thus to $F \cap A$, for each $\lambda \in (0, 1]$. Since $(1-\lambda)p + \lambda u$ converges to p , as λ goes to 0 and $\lambda > 0$, it follows that $p \in \text{cl}(F \cap A)$. We have thus proved that $F \cap \text{cl}(A) \subseteq \text{cl}(F \cap A)$. The converse containment is trivial. \square

Lemma 2.4. *Let F be the union of finitely many closed subspaces in a real topological vector space \mathbb{E} and let Q be a convex subset of \mathbb{E} . Then either $Q \subseteq F$ or $Q \cap F$ is nowhere dense in Q .*

Proof. We first deal with the case where F is a closed subspace of \mathbb{E} . Suppose that $Q \cap F$ is not nowhere dense in Q . Since F is a closed subspace of \mathbb{E} , $Q \cap F$ is also relatively closed in Q , thus the relative interior U of $Q \cap F$ in Q is nonempty. Fix $u \in U$ and let $q \in Q$. Since Q is convex, $(1-\lambda)u + \lambda q \in Q$ for every $\lambda \in [0, 1]$. Since U is a relative neighborhood of u in Q , it follows that $(1-\lambda)u + \lambda q$ belongs to U , thus to F , for some $\lambda \in (0, 1]$. Since $\{u, (1-\lambda)u + \lambda q\} \subseteq F$ with $\lambda > 0$, it follows that $q \in F$, therefore completing the proof that $Q \subseteq F$.

Now in the general case, $F = \bigcup_{i=1}^n F_i$, where each F_i is a closed subspace of \mathbb{E} . If $Q \not\subseteq F$, then $Q \not\subseteq F_i$, thus, by the paragraph above, $Q \cap F_i$ is nowhere dense in Q , for all $i \in [n]$. Therefore, $Q \cap F = \bigcup_{i=1}^n (Q \cap F_i)$ is also nowhere dense in Q . \square

3. ABELIAN LATTICE-ORDERED GROUPS

In this section we will survey some well known facts about ℓ -groups, the functor Id_c , from Abelian ℓ -groups to distributive lattices with zero, and the Baker-Beynon duality. A key point is that for a ℓ -homomorphism $f: A \rightarrow B$ of Abelian ℓ -groups, the map $\text{Id}_c f: \text{Id}_c A \rightarrow \text{Id}_c B$ is a special kind of 0-lattice homomorphism, which we call a *closed map* (cf. Lemma 3.2).

Our basic reference on ℓ -groups will be Bigard, Keimel, and Wolfenstein [5].

In any ℓ -group G , we set $x^+ \stackrel{\text{def}}{=} x \vee 0$, $x^- \stackrel{\text{def}}{=} (-x) \vee 0$, and $|x| \stackrel{\text{def}}{=} x \vee (-x)$. We denote by $\text{Id } G$ the lattice of all ℓ -ideals of an Abelian ℓ -group G , and by $\text{Id}_c G$ the lattice of all finitely generated ℓ -ideals of G . Denoting by $\langle a_1, \dots, a_n \rangle$ (or $\langle a_1, \dots, a_n \rangle_G$ in case G needs to be specified) the ℓ -ideal generated by $\{a_1, \dots, a_n\}$, $\text{Id}_c G$ consists of all the ℓ -ideals of the form $\langle a_1, \dots, a_n \rangle$. Setting $a \stackrel{\text{def}}{=} \sum_{i=1}^n |a_i|$, observe that $\langle a_1, \dots, a_n \rangle = \langle a \rangle = \{x \in G \mid |x| \propto a\}$. In particular, $\text{Id}_c G = \{\langle a \rangle \mid a \in G^+\}$. Due to the elementary properties of ℓ -groups, the join and meet operation on $\text{Id}_c G$ are given by

$$\langle x \rangle \vee \langle y \rangle = \langle x \vee y \rangle = \langle x + y \rangle, \quad \langle x \rangle \cap \langle y \rangle = \langle x \wedge y \rangle, \quad \text{for all } x, y \in G^+. \quad (3.1)$$

In particular, $\text{Id}_c G$ is a distributive lattice with zero.

The following lemma is well known, see, for example, Bigard, Keimel, and Wolfenstein [5, Section 2.3].

Lemma 3.1. *The following statements hold, for every Abelian ℓ -group G :*

- (1) *For every ℓ -ideal I of G , the set $\mathbf{I} \stackrel{\text{def}}{=} \{\langle x \rangle \mid x \in I \cap G^+\}$ is an ideal of $\text{Id}_c G$. Furthermore, the assignment $\langle x \rangle_I \mapsto \langle x \rangle_G$ defines an isomorphism from $\text{Id}_c I$ onto \mathbf{I} .*
- (2) *For every ideal \mathbf{I} of $\text{Id}_c G$, the set $I \stackrel{\text{def}}{=} \{x \in G \mid \langle x \rangle \in \mathbf{I}\}$ is an ℓ -ideal of G .*
- (3) *The assignments $I \mapsto \mathbf{I}$ and $\mathbf{I} \mapsto I$, in (1) and (2) above, are mutually inverse.*

For an ℓ -homomorphism $f: G \rightarrow H$ between Abelian ℓ -groups, it follows easily from (3.1) that the map $\text{Id}_c f: \text{Id}_c G \rightarrow \text{Id}_c H$, $\langle x \rangle \mapsto \langle f(x) \rangle$ is well defined, and is a 0-lattice homomorphism. This defines a functor Id_c , from Abelian ℓ -groups with ℓ -homomorphisms, to distributive 0-lattices with 0-lattice homomorphisms. This functor preserves direct limits and finite direct products.

A map \mathbf{f} separates zero if $\mathbf{f}^{-1}\{0\} = \{0\}$.

Lemma 3.2. *Let A and B be Abelian ℓ -groups and let $f: A \rightarrow B$ be an ℓ -homomorphism. Then the map $\mathbf{f} \stackrel{\text{def}}{=} \text{Id}_c f$ has the following properties:*

- (1) *\mathbf{f} is a 0-lattice homomorphism.*
- (2) *Let $\mathbf{a}_0, \mathbf{a}_1 \in \text{Id}_c A$ and let $\mathbf{b} \in \text{Id}_c B$. If $\mathbf{f}(\mathbf{a}_0) \subseteq \mathbf{f}(\mathbf{a}_1) \vee \mathbf{b}$, then there exists $\mathbf{a} \in \text{Id}_c A$ such that $\mathbf{a}_0 \subseteq \mathbf{a}_1 \vee \mathbf{a}$ and $\mathbf{f}(\mathbf{a}) \subseteq \mathbf{b}$. We say that the map \mathbf{f} is closed.*
- (3) *\mathbf{f} separates zero iff it is one-to-one, iff f is one-to-one.*

The terminology *closed maps*, in Lemma 3.2(2) above, is borrowed from Iberkleid, Martínez, and McGovern [26].

Proof. Ad (1). This follows immediately from (3.1).

Ad (2). Let $\mathbf{a}_0, \mathbf{a}_1 \in A^+$ and $\mathbf{b} \in B^+$ such that each $\mathbf{a}_i = \langle a_i \rangle_A$ and $\mathbf{b} = \langle b \rangle_B$. Then the assumption $\mathbf{f}(\mathbf{a}_0) \subseteq \mathbf{f}(\mathbf{a}_1) \vee \mathbf{b}$ means that there exists a positive integer n such that $f(a_0) \leq n(f(a_1) + b)$, which, since $b \geq 0$, is equivalent to $(f(a_0) - nf(a_1))^+ \leq nb$, that is, since f is an ℓ -homomorphism, $f((a_0 - na_1)^+) \leq nb$. Therefore, setting $\mathbf{a} \stackrel{\text{def}}{=} \langle (a_0 - na_1)^+ \rangle_A$, we get $\mathbf{a}_0 \subseteq \mathbf{a}_1 \vee \mathbf{a}$ and $\mathbf{f}(\mathbf{a}) \subseteq \mathbf{b}$.

Ad (3). Suppose first that f is one-to-one and let $\mathbf{a}_0, \mathbf{a}_1 \in \text{Id}_c A$ such that $\mathbf{f}(\mathbf{a}_0) \subseteq \mathbf{f}(\mathbf{a}_1)$. Write $\mathbf{a}_i = \langle a_i \rangle_A$, where $a_i \in A^+$. There exists a positive integer n such that $f(a_0) \leq nf(a_1)$, that is, $f((a_0 - na_1)^+) = 0$. Since f is one-to-one, this is

equivalent to $(a_0 - na_1)^+ = 0$, that is, $a_0 \leq na_1$; whence $\mathbf{a}_0 \subseteq \mathbf{a}_1$, thus completing the proof that \mathbf{f} is one-to-one.

It is trivial that if \mathbf{f} is one-to-one, then it separates zero.

Suppose, finally, that \mathbf{f} separates zero. For every $a \in A$, if $f(a) = 0$, then $\mathbf{f}(\langle a \rangle_A) = \langle f(a) \rangle_B = 0$, thus, since \mathbf{f} separates zero, $\langle a \rangle_A = 0$, that is, $a = 0$. Since f is a group homomorphism, it follows that f is one-to-one. \square

This motivates the following definition.

Definition 3.3. A distributive lattice with zero is ℓ -representable if it is isomorphic to $\text{Id}_c G$ for some Abelian ℓ -group G . More generally, say that a diagram \vec{D} , of distributive lattices with zero and 0-lattice homomorphisms, is ℓ -representable, if it is isomorphic to $\text{Id}_c \vec{G}$ for a diagram \vec{G} , of Abelian ℓ -groups and ℓ -homomorphisms.

Example 3.4. Using Lemma 3.2(2), it is easy to construct an example of a 0-sublattice \mathbf{A} of a finite distributive lattice \mathbf{B} , both ℓ -representable, such that the inclusion map from \mathbf{A} into \mathbf{B} is not ℓ -representable: just define \mathbf{B} as the square $\mathbf{2}^2$, and \mathbf{A} as any of the two 3-element chains in \mathbf{B} .

Another example, this time using Lemma 3.2(3), of a non- ℓ -representable 0-lattice homomorphism between finite ℓ -representable distributive lattices, is the following: denote by $\mathbf{2}$ the two-element chain and by $\mathbf{3}$ the three-element chain. Then the unique zero-separating map $\mathbf{f}: \mathbf{3} \rightarrow \mathbf{2}$ is a surjective 0-lattice homomorphism. Since \mathbf{f} is zero-separating but not one-to-one, it is not ℓ -representable.

Lemma 3.5. *Let G be an Abelian ℓ -group, let S be a distributive lattice with zero, and let $\varphi: \text{Id}_c G \rightarrow S$ be a closed surjective $(\vee, 0)$ -homomorphism. Then $I = \underset{\text{def}}{\{x \in G \mid \varphi(\langle x \rangle) = 0\}}$ is an ℓ -ideal of G , and there is a unique order-isomorphism $\psi: \text{Id}_c(G/I) \rightarrow S$ such that $\psi(\langle x/I \rangle) = \varphi(\langle x \rangle)$ for every $x \in G^+$. In particular, S is a lattice and ψ is a lattice isomorphism.*

Proof. It is straightforward to verify that I is an ℓ -ideal of G and that there is a unique map $\psi: \text{Id}_c(G/I) \rightarrow S$ such that $\psi(\langle x/I \rangle) = \varphi(\langle x \rangle)$ for every $x \in G^+$. Since φ is a surjective $(\vee, 0)$ -homomorphism, so is ψ . It remains to verify that ψ is an order-embedding.

Let $x, y \in G^+$ such that $\psi(\langle x/I \rangle) \leq \psi(\langle y/I \rangle)$. This means that $\varphi(\langle x \rangle) \leq \varphi(\langle y \rangle)$, thus, since φ is a closed map, there exists $z \in \text{Id}_c G$ such that $\langle x \rangle \subseteq \langle y \rangle \vee z$ and $\varphi(z) = 0$. Writing $z = \langle z \rangle$, for $z \in G^+$, this means that $z \in I$ and $x \leq ny + nz$ for some positive integer n . Therefore, $x/I \leq n(y/I)$, so $\langle x/I \rangle \subseteq \langle y/I \rangle$. \square

It is well known that every free Abelian ℓ -group is a subdirect power of \mathbb{Z} , thus, *a fortiori*, of \mathbb{R} ; this result originates in Henriksen and Isbell [23], Weinberg [43]. For a set I , denote by $\mathbb{R}^{(I)}$ the set of all families $x = (x_i \mid i \in I)$ of real numbers, such that the *support* of x , defined as $\underset{\text{def}}{\text{supp}(x)} = \{i \in I \mid x_i \neq 0\}$, is finite.

Proposition 3.6. *Let I be a set and denote by $F_\ell(I)$ the ℓ -subgroup of $\mathbb{R}^{\mathbb{R}^{(I)}}$ generated by the canonical projections $p_i: \mathbb{R}^{(I)} \rightarrow \mathbb{R}$, for $i \in I$. Then $(F_\ell(I), (p_i \mid i \in I))$ is the free Abelian ℓ -group on I .*

Note. Proposition 3.6 is usually stated with \mathbb{Z}^I , or \mathbb{R}^I , instead of $\mathbb{R}^{(I)}$. The result of Proposition 3.6 is not affected by that change.

The description of free Abelian ℓ -groups, given by Proposition 3.6, yields a convenient description of the ℓ -ideals of such ℓ -groups. This description is contained in the *Baker-Beynon duality*, see Baker [1], Beynon [3, 4]. The following consequence, of that duality, involves the description of $F_\ell(I)$ given in Proposition 3.6.

Proposition 3.7. *Let I be a set, and denote by $\text{Lat}(I)$ the sublattice, of the powerset lattice of $\mathbb{R}^{(I)}$, generated by all sets $\llbracket f > 0 \rrbracket$, where f is a linear combination, with integer coefficients, of the projections $p_i: \mathbb{R}^{(I)} \rightarrow \mathbb{R}$. Then there is a unique isomorphism $\iota: \text{Id}_c F_\ell(I) \rightarrow \text{Lat}(I)$ such that $\iota(\langle f \rangle) = \llbracket f \neq 0 \rrbracket$ whenever $f \in F_\ell(I)$.*

Note. The empty set $\emptyset = \llbracket 0 > 0 \rrbracket$ belongs to $\text{Lat}(I)$, which is thus a 0-sublattice of the powerset lattice of $\mathbb{R}^{(I)}$. On the other hand, for every linear combination f of the projections, the subset $\llbracket f > 0 \rrbracket$ omits the origin of $\mathbb{R}^{(I)}$. It follows that $\mathbb{R}^{(I)}$ does not belong to $\text{Lat}(I)$, which is thus not a 1-sublattice of the powerset of $\mathbb{R}^{(I)}$.

4. COMPLETELY NORMAL SPACES, SPECTRAL SPACES

In this section we shall survey some basic facts and examples about completely normal spaces and (generalized) spectral spaces. We will also reduce the MV-spectrum problem to a lattice-theoretical problem (cf. Lemma 4.7). Recall that $\mathcal{O}(X)$ denotes the lattice of all open subsets in a topological space X . Moreover, we shall denote by $\mathcal{K}(X)$ the set of all compact open subsets of X (i.e., the compact members of the lattice $\mathcal{O}(X)$, see Section 2.2).

Definition 4.1. A topological space X is

- T_0 if for any distinct points $x, y \in X$, there is an open subset of X containing one element of $\{x, y\}$ and not the other;
- *sober* if every join-irreducible member, of the lattice of all closed subsets of X , is the closure of a unique singleton;
- *generalized spectral* if it is sober, $\mathcal{K}(X)$ is a basis for the topology of X , and the intersection of any two compact open subsets of X is compact;
- *spectral* if it is both generalized spectral and compact.

The *specialization order* on a T_0 space X is defined by letting $x \leq y$ hold if y belongs to the closure of $\{x\}$, for all $x, y \in X$.

In particular, the uniqueness part, in the definition of sobriety stated above, ensures that every sober space is T_0 (not all references assume this). The statement, that $\mathcal{K}(X)$ is a basis for the topology of X , is equivalent to $\mathcal{O}(X)$ be an algebraic lattice (cf. Section 2.2 for terminology).

All generalized spectral spaces arise from distributive lattices with zero, as follows (see Johnstone [27, Section II.3] for more details). The *spectrum* of a distributive lattice D with zero, denoted by $\text{Spec } D$, is the set of all prime ideals of D , endowed with the topology whose open sets are exactly the subsets $\Omega_X \stackrel{\text{def}}{=} \{P \in \text{Spec } D \mid X \not\subseteq P\}$, for $X \subseteq D$. Denoting by $\langle X \rangle$ the ideal of D generated by X , it is obvious that $\Omega_X = \Omega_{\langle X \rangle}$. Moreover, it follows from Stone's representation Theorem, for distributive lattices, that every ideal I of D is the intersection of all prime ideals containing it; whence Ω_I characterizes I . The compact open subsets of $\text{Spec } D$ are exactly the $\Omega_{\{a\}}$, for $a \in D$; and the assignment $a \mapsto \Omega_{\{a\}}$ defines an order-isomorphism. In particular, $D \cong \mathcal{K}(\text{Spec } D)$. For prime ideals P and Q of D , $P \leq Q$ (for the specialization order) iff $P \subseteq Q$.

Proposition 4.2. *A topological space X is generalized spectral (resp., spectral) iff it is homeomorphic to the spectrum of a distributive lattice D with zero (resp., a bounded distributive lattice). In such a case, $D \cong \mathcal{K}(X)$.*

The ℓ -spectrum, $\text{Spec}_\ell G$, of an Abelian ℓ -group G can be defined the same way as the spectrum of a distributive lattice with zero. Namely, $\text{Spec}_\ell G$ consists of all prime ℓ -ideals of G , and its closed sets are the $V_I \stackrel{\text{def}}{=} \{P \in \text{Spec}_\ell G \mid I \subseteq P\}$, for ℓ -ideals I of G . Hence, by Lemma 3.1, the ℓ -spectrum of the ℓ -group G is homeomorphic to the spectrum of the distributive lattice $\text{Id}_c G$. By Proposition 4.2, this reduces the description of ℓ -spectra of Abelian ℓ -groups to the one of ℓ -representable distributive lattices with zero.

Similarly, *MV-spectra* of MV-algebras are, *via* Mundici's equivalence [33], the same as ℓ -spectra of Abelian ℓ -groups with unit (cf. Cignoli and Torrens [11, Corollary 1.3]). If G is an Abelian ℓ -group with unit u , then the ℓ -spectrum of G is naturally isomorphic to the MV-spectrum of the MV-algebra $[0, u]$.

Definition 4.3.

- (1) A distributive lattice D with zero is *completely normal* if for all $a, b \in D$, there exist $x, y \in D$ such that $a \leq b \vee x$, $b \leq a \vee y$, and $x \wedge y = 0$.
- (2) A generalized spectral space X is *completely normal* if the specialization order on X is a root system.

The reader should be warned that the literature contains several non-equivalent definitions of (complete) normality, as well for lattices as for topological spaces:

- While our choice of terminology in Definition 4.3(1) is consistent with Johnstone [27], Cignoli [9] would rather call such lattices “dually completely normal”; and Snodgrass and Tsinakis [37, 38] would call them “relatively normal”.
- Complete normality, of a topological space X , is sometimes defined by stating that every subspace of X — or, equivalently, every open subspace of X — is normal (cf. Munkres [35, Exercise IV.32.6]). Equivalently, the lattice $\mathcal{O}(X)$, of all open subsets of X , is completely normal in the sense of Definition 4.3(1). By the following Proposition 4.4, this implies complete normality as stated in Definition 4.3(2). However, as witnessed by the following Example 4.5, the converse implication does not hold, even for spectral spaces; that is, the two concepts of complete normality are not equivalent.

The following result is a restatement of Monteiro [32, Théorème V.3.1], see also Cignoli [9, Proposition 1.9]. We include a proof for convenience.

Proposition 4.4. *A generalized spectral space X is completely normal, in the sense of Definition 4.3(1), iff its lattice $\mathcal{K}(X)$, of all compact open subsets, is completely normal.*

Proof. By Proposition 4.2, it suffices to prove that a distributive lattice D with zero is completely normal iff $\text{Spec } D$ is a completely normal topological space (in the sense of Definition 4.3). Suppose first that D is completely normal and let P, Q, R be prime ideals of D such that P is contained in both Q and R , and Q and R are incomparable. Pick $a \in Q \setminus R$ and $b \in R \setminus Q$. By assumption, there are $x, y \in D$ such that $a \leq b \vee x$, $b \leq a \vee y$, and $x \wedge y = 0$. Necessarily, $x \notin R$ and $y \notin Q$, thus $x, y \notin P$, in contradiction with $x \wedge y = 0$ together with the primeness of P .

Suppose, conversely, that $\text{Spec } D$ is completely normal and let $a, b \in D$. We must prove that 0 belongs to the filter $C \stackrel{\text{def}}{=} \uparrow \{x \wedge y \mid (x, y) \in (a \ominus b) \times (b \ominus a)\}$ (cf. (2.1) for notation). Suppose otherwise. By a well known theorem of Stone (cf. Grätzer [22, Theorem 115]), there is a prime ideal P of D such that $C \cap P = \emptyset$. We claim that $\uparrow a \cap (P \vee \downarrow b) = \emptyset$ (where $P \vee \downarrow b$ denotes the join of P and $\downarrow b$ in the ideal lattice of D). Otherwise, there is $x \in P$ such that $a \leq b \vee x$; that is, $x \in a \ominus b$, thus $x \in C$, and thus $x \notin P$, a contradiction. This proves our claim. By the above-mentioned Stone's Theorem, there is a prime ideal Q such that $P \vee \downarrow b \subseteq Q$ and $Q \cap \uparrow a = \emptyset$; that is, $P \subseteq Q$, $b \in Q$, and $a \notin Q$. Likewise, there is a prime ideal R such that $P \subseteq R$, $a \in R$, and $b \notin R$. In particular, Q and R are incomparable, and they both contain P , which contradicts our assumption. \square

Example 4.5. *A second countable spectral space X satisfying the following conditions:*

- (1) *The lattice $\mathcal{K}(X)$ is a self-dual Heyting algebra.*
- (2) *The lattice $\mathcal{K}(X)$ is completely normal.*
- (3) *The lattice $\mathcal{O}(X)$ is not completely normal.*

Proof. Consider the finite chain $\mathbf{3} \stackrel{\text{def}}{=} \{0, 1, 2\}$. The set D , of all eventually constant sequences of elements of $\mathbf{3}$, is a countable, bounded sublattice of $\mathbf{3}^\omega$. Since $\mathbf{3}$ is a completely normal, self-dual Heyting algebra, so is D .

We claim that the ideal lattice $\text{Id } D$ of D is not completely normal. Write the elements of D in the form $(1 \cdot X) \sqcup (2 \cdot Y)$, for disjoint subsets X and Y of ω , each of them either finite or cofinite. Recalling the usual convention $n = \{0, \dots, n-1\}$, we set

$$a_n \stackrel{\text{def}}{=} 2 \cdot n \text{ and } b_n \stackrel{\text{def}}{=} 1 \cdot (\omega \setminus n), \quad \text{for all } n \in \omega.$$

Moreover, denote by \mathbf{a} the ideal of D generated by $\{a_n \mid n \in \omega\}$. Suppose that there are ideals \mathbf{u}, \mathbf{v} of D such that $\downarrow b_0 \subseteq \mathbf{a} \vee \mathbf{v}$, $\mathbf{a} \subseteq \downarrow b_0 \vee \mathbf{u}$, and $\mathbf{u} \cap \mathbf{v} = \{0\}$. The first condition implies that $b_m \in \mathbf{v}$ for some $m \in \omega$. The second condition implies that $a_n \in \mathbf{u}$ for all n . In particular, $a_{m+1} \in \mathbf{u}$, thus the element $1 \cdot \{m\} = a_{m+1} \wedge b_m$ belongs to $\mathbf{u} \cap \mathbf{v}$, a contradiction.

By Proposition 4.2, the spectrum X of D is a spectral space with $D \cong \mathcal{K}(X)$; hence the lattice $\mathcal{K}(X)$ is completely normal. On the other hand, $\mathcal{O}(X)$ is isomorphic to the ideal lattice of $\mathcal{K}(X)$, thus to the ideal lattice of D . By the above, this lattice is not completely normal. \square

As already mentioned in Section 1.2, the ℓ -spectrum of any Abelian ℓ -group is completely normal (see, for example, Bigard, Keimel, and Wolfenstein [5, Proposition 10.1.11]). It is worthwhile to pinpoint the lattice-theoretical content of that result.

Lemma 4.6. *Let G be an Abelian ℓ -group. Then $\text{Id}_c G$ is completely normal.*

Proof. Let $\mathbf{a}, \mathbf{b} \in \text{Id}_c G$. There are $a, b \in G^+$ such that $\mathbf{a} = \langle a \rangle$ and $\mathbf{b} = \langle b \rangle$. Set $\mathbf{x} \stackrel{\text{def}}{=} \langle a - (a \wedge b) \rangle$ and $\mathbf{y} \stackrel{\text{def}}{=} \langle b - (a \wedge b) \rangle$. Then $\mathbf{a} \subseteq \mathbf{b} \vee \mathbf{x}$, $\mathbf{b} \subseteq \mathbf{a} \vee \mathbf{y}$, and $\mathbf{x} \cap \mathbf{y} = \{0\}$. \square

Lemma 4.7. *A topological space X is homeomorphic to the ℓ -spectrum of an Abelian ℓ -group iff it is generalized spectral and the lattice $\mathcal{K}(X)$ is ℓ -representable.*

Proof. For every Abelian ℓ -group G , the ℓ -spectrum X of G is isomorphic to the spectrum of the distributive lattice $\text{Id}_c G$, thus it is generalized spectral (cf. Proposition 4.2). Moreover, the lattice $\mathcal{K}(X) \cong \text{Id}_c G$ is ℓ -representable.

Let, conversely, X be a generalized spectral space and let G be an Abelian ℓ -group such that $\mathcal{K}(X) \cong \text{Id}_c G$. Then $\mathcal{O}(X)$ is isomorphic to the ideal lattice of $\mathcal{K}(X)$, which is isomorphic to the ideal lattice of $\text{Id}_c G$, which is isomorphic to the ideal lattice of G (cf. Lemma 3.1), which is isomorphic to $\mathcal{O}(\text{Spec}_\ell G)$. Since X and $\text{Spec}_\ell G$ are both sober spaces, it follows (cf. Johnstone [27, Section II.1]) that $X \cong \text{Spec}_\ell G$. \square

5. NON- ℓ -REPRESENTABILITY RESULTS

In this section we shall show that the class of ℓ -representable distributive lattices is neither first-order, nor closed under infinite products. Recall that lattices with countably based differences are introduced in Section 2.2. The following result is a restatement, in terms of lattices of principal ℓ -ideals, of Cignoli, Gluschankof, and Lucas [10, Theorem 2.2]; see also Iberkleid, Martínez, and McGovern [26, Proposition 4.1.2]. We include a proof for convenience.

Lemma 5.1. *Let G be a Abelian ℓ -group. Then the lattice $\text{Id}_c G$ has countably based differences.*

Proof. Let $\mathbf{a}, \mathbf{b} \in \text{Id}_c G$, and pick $a, b \in G^+$ such that $\mathbf{a} = \langle a \rangle$ and $\mathbf{b} = \langle b \rangle$. Set $\mathbf{c}_n = \langle (a - nb)^+ \rangle$, for every nonnegative integer n . From $a \leq nb + (a - nb)^+$ it follows that $\mathbf{a} \leq \mathbf{b} \vee \mathbf{c}_n$. Let $\mathbf{x} \in \text{Id}_c G$ such that $\mathbf{a} \leq \mathbf{b} \vee \mathbf{x}$. Let $x \in G^+$ such that $\mathbf{x} = \langle x \rangle$. There exists a nonnegative integer n such that $a \leq nb + nx$. Since $x \in G^+$, it follows that $(a - nb)^+ \leq nx$; whence $\mathbf{c}_n \leq \mathbf{x}$. \square

Example 5.2. *A countable Abelian ℓ -group G , with order-unit, such that $\text{Id}_c G$ is not a dual Heyting algebra.*

Proof. Let G consist of all maps $x: \omega \rightarrow \mathbb{Z}$ such that there are (necessarily unique) $\alpha, \beta \in \mathbb{Z}$ such that $x(n) = \alpha n + \beta$ for all large enough n . Then G , ordered componentwise, is an ℓ -subgroup of \mathbb{Z}^ω . The constant function a , with value 1, and the identity function b on ω both belong to G^+ , $a + b$ is an order-unit of G , and there is no least $\mathbf{x} \in \text{Id}_c G$ such that $\langle b \rangle \subseteq \langle a \rangle \vee \mathbf{x}$. \square

It is easy to see that the class of all ℓ -representable distributive lattices is closed under finite direct products. We shall now show that this observation does not extend to infinite products.

Proposition 5.3. *Let D be a distributive lattice with zero. If D is not a dual Heyting algebra, then D^ω is not ℓ -representable.*

Proof. Denote by $\varepsilon: D \hookrightarrow D^\omega$ the diagonal embedding and suppose that D^ω is ℓ -representable. Since D is isomorphic to an ideal of D^ω , it is also ℓ -representable, thus, by Lemma 5.1, D has countably based differences. On the other hand, since D is not a dual Heyting algebra, there are $a, b \in D$ such that the set $a \ominus b$ (cf. (2.1)) has no least element. Hence, the set $a \ominus b$ has a strictly descending coinital sequence $(c_n \mid n \in \omega)$.

Now by Lemma 5.1, $D^{(\omega)}$ has countably based differences. In particular, the set $\varepsilon(a) \ominus \varepsilon(b)$ has a countable descending coinital sequence $(\mathbf{e}_n \mid n \in \omega)$. For all

$n, k \in \omega$, $a \leq b \vee e_n(k)$, thus there exists $f(n, k) \in \omega$ such that $c_{f(n, k)} \leq e_n(k)$. Set $\mathbf{x} \stackrel{\text{def}}{=} (c_{f(n, n)+1} \mid n \in \omega)$. Since $\varepsilon(a) \leq \varepsilon(b) \vee \mathbf{x}$, there exists $n \in \omega$ such that $e_n \leq \mathbf{x}$. It follows that $c_{f(n, n)} \leq e_n(n) \leq \mathbf{x}(n) = c_{f(n, n)+1}$, a contradiction. \square

By taking $D \stackrel{\text{def}}{=} \text{Id}_c G$, for the ℓ -group of Example 5.2, we obtain immediately the following.

Corollary 5.4. *The class of all ℓ -representable bounded distributive lattices is not closed under infinite products.*

The following example shows, in particular, that there is no first-order theory whose class of models is the one of all ℓ -representable bounded distributive lattices.

Example 5.5. *A non- ℓ -representable bounded distributive lattice \mathbf{D}_{ω_1} , of cardinality \aleph_1 , with a countable ℓ -representable elementary sublattice.*

Proof. Consider the finite chain $\mathbf{3} \stackrel{\text{def}}{=} \{0, 1, 2\}$. For every infinite set I , we denote by \mathbf{B}_I the set of all subsets of I that are either finite or cofinite. The set \mathbf{D}_I , of all pairs $(X, x) \in \mathbf{B}_I \times \mathbf{3}$ such that $x = 0$ iff X is finite, is a sublattice of $\mathbf{B}_I \times \mathbf{3}$.

Claim 1. *Let I be countably infinite. Then \mathbf{D}_I is ℓ -representable.*

Proof of Claim. While Claim 1 follows from our main theorem (viz., Theorem 11.1), it is easy to give an explicit representation, which we shall do now. Since $\mathbf{D}_I \cong \mathbf{D}_\omega$, it suffices to prove that \mathbf{D}_ω is ℓ -representable. Consider the Abelian ℓ -group G of Example 5.2. Let $x \in G^+$. By the definition of G , there are integers α and β such that $x(n) = \alpha n + \beta$ for all large enough n . We set

$$\rho(x) \stackrel{\text{def}}{=} \begin{cases} (\text{supp}(x), 0), & \text{if } \alpha = \beta = 0, \\ (\text{supp}(x), 1), & \text{if } \alpha = 0 \text{ and } \beta > 0, \\ (\text{supp}(x), 2), & \text{if } \alpha > 0. \end{cases}$$

It is straightforward to verify that $x \times y$ iff $\rho(x) \leq \rho(y)$, for all $x, y \in G^+$. Furthermore, the range of ρ is equal to \mathbf{D}_ω , thus ρ induces an isomorphism from $\text{Id}_c G$ onto \mathbf{D}_ω . \square Claim 1.

Claim 2. *The lattice \mathbf{D}_{ω_1} does not have countably based differences. In particular, it is not ℓ -representable.*

Proof of Claim. The elements $\mathbf{a} \stackrel{\text{def}}{=} (\omega_1, 1)$ and $\mathbf{b} \stackrel{\text{def}}{=} (\omega_1, 2)$ both belong to \mathbf{D}_{ω_1} . Furthermore, the set $\mathbf{b} \ominus \mathbf{a} = \{(X, 2) \mid X \subseteq \omega_1 \text{ cofinite}\}$ has no countable coinitial subset. The second part of our claim follows from Lemma 5.1. \square Claim 2.

For infinite subsets I and J of ω_1 with $I \subseteq J$, we set

$$\varepsilon_I^J(X, x) \stackrel{\text{def}}{=} \begin{cases} (X, x), & \text{if } X \text{ is finite,} \\ (X \cup (J \setminus I), x), & \text{if } X \text{ is cofinite,} \end{cases} \quad \text{for every } (X, x) \in \mathbf{D}_I.$$

Then ε_I^J is a 0, 1-lattice embedding from \mathbf{D}_I into \mathbf{D}_J , and the ε_I^J form a direct system of bounded distributive lattices and 0, 1-lattice embeddings, with

$$\varepsilon_\lambda^{\omega_1}[\mathbf{D}_\lambda] = \bigcup \left(\varepsilon_\xi^{\omega_1}[\mathbf{D}_\xi] \mid \omega \leq \xi < \lambda \right), \quad \text{for every limit ordinal } \lambda \leq \omega_1.$$

By the Löwenheim-Skolem Theorem (cf. Chang and Keisler [8]), the set C , of all limit ordinals $\lambda < \omega_1$ such that $\varepsilon_\lambda^{\omega_1}[\mathbf{D}_\lambda]$ is an elementary sublattice of \mathbf{D}_{ω_1} , is a

closed unbounded subset of ω_1 . Pick $\lambda \in C$. Then \mathbf{D}_λ is isomorphic to $\varepsilon_\lambda^{\omega_1}[\mathbf{D}_\lambda]$, which is an elementary sublattice of \mathbf{D}_{ω_1} . \square

Note. Denote by Z the completely normal spectral space constructed by Delzell and Madden in [14, Theorem 2]. Although there is an obvious 0,1-lattice embedding from \mathbf{D}_{ω_1} into $\mathcal{K}(Z)$, it is not hard to see that the two lattices are not isomorphic. Hence, Z is not homeomorphic to the spectrum of \mathbf{D}_{ω_1} .

See also Problem 1 in Section 12.

6. CONSONENCE AND DIFFERENCE OPERATIONS

The proof of our main theorem (Theorem 11.1) will make an extensive use of the following concept of consonence, which is a local version of complete normality.

Definition 6.1. Let A and B be distributive lattices with zero.

- Elements x and y of A are *consonent*, in notation $x \sim y$, or $x \sim_A y$ if A needs to be specified, if there are $u, v \in A$ such that $x \leq y \vee u$, $y \leq x \vee v$, and $u \wedge v = 0$; then following Iberkleid, Martínez, and McGovern [26], we say that (u, v) is a *splitting* of (x, y) .
- A subset Z of A is *consonent in A* if $x \sim_A y$ for all $x, y \in Z$.
- A map $f: A \rightarrow B$ is *consonent* if $f[A]$ is consonent in B .

Observe that the definition of complete normality, as stated in Definition 4.3(1), says that a distributive lattice D with zero is completely normal iff any two elements of D are consonent.

Note. In the context of Definition 6.1, if (u, v) is a splitting of (x, y) , then so is $(u \wedge x, v \wedge y)$. Moreover, for all $u \leq x$ and $v \leq y$, (u, v) is a splitting of (x, y) iff $x \vee y = x \vee v = u \vee y$ and $u \wedge v = 0$.

Lemma 6.2. *The following statements hold, for every distributive lattice D with zero and all $a, b, c \in D$:*

- (1) $a \sim b$ iff $b \sim a$.
- (2) If either a and b are comparable or $a \wedge b = 0$, then $a \sim b$.
- (3) If $a \sim c$ and $b \sim c$, then $a \wedge b \sim c$ and $a \vee b \sim c$.

Proof. (1) is trivial.

Ad (2). If $a \leq b$, then $(a, 0)$ is a splitting of (a, b) . If $a \wedge b = 0$, then (a, b) is a splitting of (a, b) .

Ad (3). If (x, x') is a splitting of (a, c) and (y, y') is a splitting of (b, c) , then $(x \vee y, x' \wedge y')$ is a splitting of $(a \vee b, c)$ and $(x \wedge y, x' \vee y')$ is a splitting of $(a \wedge b, c)$. \square

Definition 6.3. Let L be a lattice and let S be a $(\vee, 0)$ -semilattice. A map $L \times L \rightarrow S$, $(x, y) \mapsto x \setminus y$ is an *S -valued difference operation* on L if the following statements hold:

- (D0) $x \setminus x = 0$, for all $x \in L$.
- (D1) $x \setminus z = (x \setminus y) \vee (y \setminus z)$, for all $x, y, z \in L$ such that $x \geq y \geq z$.
- (D2) $x \setminus y = (x \vee y) \setminus y = x \setminus (x \wedge y)$, for all $x, y \in L$.

We say, further, that the difference operation \setminus is *normal* if the following condition holds:

- (D3) $(x \setminus y) \wedge (y \setminus x) = 0$, for all $x, y \in L$.

Although we will need the following lemma only in case L is distributive, we found it worth noticing that it holds for arbitrary L .

Lemma 6.4. *Let L be a lattice, let S be a $(\vee, 0)$ -semilattice, and let \setminus be an S -valued difference operation on L . Then $x \setminus z \leq (x \setminus y) \vee (y \setminus z)$, for all $x, y, z \in S$ (triangle inequality). Furthermore, the map $(x, y) \mapsto x \setminus y$ is isotone in x and antitone in y .*

Proof. After some amount of translation, this trivially follows from Wehrung [40, Proposition 1.9]. We provide a direct proof for the reader's convenience.

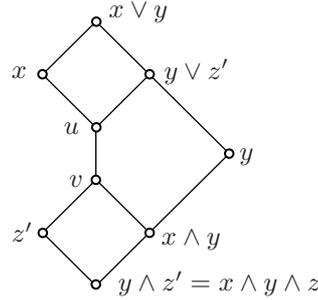


FIGURE 6.1. The sublattice generated by $\{x, y, z'\}$

Set $z' \stackrel{\text{def}}{=} x \wedge z$. The sublattice of L generated by $\{x, y, z'\}$ is represented in Figure 6.1, with $u \stackrel{\text{def}}{=} x \wedge (y \vee z')$ and $v \stackrel{\text{def}}{=} (x \wedge y) \vee z'$. Since

$$\begin{aligned} x \setminus z &= x \setminus z' && \text{(by (D2))} \\ &= (x \setminus u) \vee (u \setminus v) \vee (v \setminus z') && \text{(by (D1))}, \end{aligned}$$

it suffices to prove that $x \setminus u$, $u \setminus v$, and $v \setminus z'$ are all below $(x \setminus y) \vee (y \setminus z)$. By using (D2), (D1), and (D2) again, we obtain

$$x \setminus u = (x \vee y) \setminus (y \vee z') \leq (x \vee y) \setminus y = x \setminus y.$$

By using (D1), (D2), (D1), (D2), we obtain

$$u \setminus v = u \setminus (x \wedge y) = (y \vee z') \setminus y \leq (x \vee y) \setminus y = x \setminus y.$$

By using (D2), the equation $y \wedge z' = (x \wedge y) \wedge (y \wedge z)$, (D2), (D1), (D2), we get

$$v \setminus z' = (x \wedge y) \setminus (y \wedge z') = (x \wedge y) \setminus (y \wedge z) \leq y \setminus (y \wedge z) = y \setminus z,$$

thus completing the proof of the triangle inequality.

Now let $x_1, x_2, y \in L$ with $x_1 \leq x_2$. By using (D2) and (D0), we get

$$x_1 \setminus x_2 = x_1 \setminus (x_1 \wedge x_2) = x_1 \setminus x_1 = 0,$$

thus, by the triangle inequality, $x_1 \setminus y \leq (x_1 \setminus x_2) \vee (x_2 \setminus y) = x_2 \setminus y$. The proof, that $y_1 \leq y_2$ implies $x \setminus y_2 \leq x \setminus y_1$, is similar. \square

Lemma 6.5. *Let L be a finite lattice, let S be a $(\vee, 0)$ -semilattice, and let \setminus be an S -valued difference operation on L . Then the following statement holds:*

$$a \setminus b = \bigvee (p \setminus p_* \mid p \in \text{Ji}L, p \leq a, p \not\leq b), \quad \text{for all } a, b \in L. \quad (6.1)$$

Proof. Since neither side of (6.1) is affected by changing the pair (a, b) to $(a, a \wedge b)$, we may assume that $a \geq b$, and then prove (6.1) by induction on a . The result is trivial for $a = b$ (use (D0)). Dealing with the induction step, suppose that $a > b$. Pick $a' \in L$ such that $b \leq a'$ and a' is a lower cover of a . The set $\{x \in L \mid x \leq a \text{ and } x \not\leq a'\}$ has a minimal element p . Necessarily, p is join-irreducible and $p_* \leq a'$, so $[p_*, p]$ projects up to $[a', a]$. By (D2), $p \searrow p_* = a \searrow a'$. Moreover, by the induction hypothesis,

$$a' \searrow b = \bigvee (q \searrow q_* \mid q \in \text{Ji } L, q \leq a', q \not\leq b).$$

Using (D1), we get $a \searrow b = (a \searrow a') \vee (a' \searrow b) \geq \bigvee (q \searrow q_* \mid q \in \text{Ji } L, q \leq a, q \not\leq b)$. For the converse inequality, for any $q \in \text{Ji } L$ such that $q \leq a$ and $q \not\leq b$, observe that $b \leq q^\dagger$, thus

$$\begin{aligned} q \searrow q_* &= q \searrow q^\dagger && \text{(because } q_* = q \wedge q^\dagger \text{ and by (D2))} \\ &\leq a \searrow b && \text{(use the second statement of Lemma 6.4),} \end{aligned}$$

thus completing the proof of the desired inequality. \square

Lemma 6.6. *Let D be a distributive lattice, let S be a $(\vee, 0)$ -semilattice, let \searrow be an S -valued difference operation on D . Then for all $a_1, b_1, a_2, b_2 \in D$, if $a_1 \leq b_1 \vee a_2$ and $a_1 \wedge b_2 \leq b_1$ (within D), then $a_1 \searrow b_1 \leq a_2 \searrow b_2$ (within S).*

Proof. Changing each b_i to $a_i \wedge b_i$ weakens the premise of Lemma 6.6, and, by (D2), does not affect its conclusion. Hence, we may assume that $a_i \geq b_i$, for $i \in \{1, 2\}$. Set $u_1 \stackrel{\text{def}}{=} a_1 \wedge a_2$, $v_1 \stackrel{\text{def}}{=} b_1 \wedge a_2$, $u_2 \stackrel{\text{def}}{=} u_1 \vee b_2$, $v_2 \stackrel{\text{def}}{=} v_1 \vee b_2$. Then the interval $[b_1, a_1]$ projects down to $[v_1, u_1]$, which projects up to $[v_2, u_2]$, which is contained in $[b_2, a_2]$ (cf. Figure 6.2). Since, by (D2), the difference operation gives the same

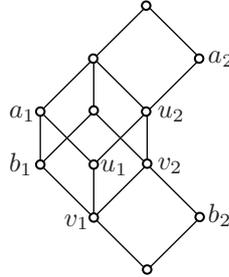


FIGURE 6.2. The sublattice of D generated by $\{a_1, b_1, a_2, b_2\}$

value to projective intervals, it follows that $a_1 \searrow b_1 = u_1 \searrow v_1 = u_2 \searrow v_2$. Moreover, by (D1), $a_2 \searrow b_2 = (a_2 \searrow u_2) \vee (u_2 \searrow v_2) \vee (v_2 \searrow b_2) \geq u_2 \searrow v_2$, so $a_2 \searrow b_2 \geq a_1 \searrow b_1$. \square

The following lemma will be a crucial source of difference operations throughout the present paper. Although its proof is a straightforward exercise, we present it nevertheless, due to its importance in the paper.

Lemma 6.7. *Let D be a sublattice of a finite distributive lattice S . We set*

$$x \searrow_S y \stackrel{\text{def}}{=} \bigwedge (s \in S \mid x \leq y \vee s), \quad \text{for all } x, y \in D. \quad (6.2)$$

Then $x \setminus_S y$ is the least $s \in S$ such that $x \leq y \vee s$. Furthermore, the operation \setminus_S is an S -valued difference operation on D , and if D is consonant in S , then \setminus_S is a normal difference operation on D .

Note. In their paper [15], Di Nola and Grigolia call $x \setminus_S y$ the *pseudo-difference* of x and y .

Proof. It follows immediately from the distributivity of S that $x \leq y \vee (x \setminus_S y)$ for all $x, y \in D$. Hence, $x \setminus_S y$ is the least $s \in S$ such that $x \leq y \vee s$.

Trivially, $x \setminus_S x$ is the zero element of S , for every $x \in D$.

Let $x, y, z \in D$ with $x \geq y \geq z$, set $u \stackrel{\text{def}}{=} x \setminus_S y$ and $v \stackrel{\text{def}}{=} y \setminus_S z$. Then for every $s \in S$, the inequality $x \leq z \vee s$ implies $x \leq y \vee s$ (because $z \leq y$) and $y \leq z \vee s$ (because $y \leq x$), that is, $u \leq s$ and $v \leq s$. Hence, $u \vee v \leq x \setminus_S z$. Conversely, $x \leq y \vee u$ and $y \leq z \vee v$, thus $x \leq z \vee u \vee v$, and thus $x \setminus_S z \leq u \vee v$, hence completing the proof that $x \setminus_S z = u \vee v = (x \setminus_S y) \vee (y \setminus_S z)$.

Let $x, y \in D$ and let $s \in S$. Then $x \leq y \vee s$ iff $x \vee y \leq y \vee s$; thus $x \setminus_S y = (x \vee y) \setminus_S y$. Similarly, $x \leq y \vee s$ iff $x \leq (x \wedge y) \vee s$ (because S is distributive), thus $x \setminus_S y = x \setminus_S (x \wedge y)$.

So far we have proved that \setminus_S is a difference operation on D . Now suppose that D is consonant in S and let $x, y \in D$. By assumption, $x \sim_S y$, thus there are $u, v \in S$ such that $x \leq y \vee u$, $y \leq x \vee v$, and $u \wedge v = 0$. Since $x \setminus_S y \leq u$ and $y \setminus_S x \leq v$, it follows that $(x \setminus_S y) \wedge (y \setminus_S x) = 0$. \square

Lemma 6.8. *The following statements hold, for every finite distributive lattice S and all elements $a_1, a_2, a, b_1, b_2, b \in S$:*

- (1) $(a_1 \vee a_2) \setminus_S b = (a_1 \setminus_S b) \vee (a_2 \setminus_S b)$.
- (2) $a \setminus_S (b_1 \wedge b_2) = (a \setminus_S b_1) \vee (a \setminus_S b_2)$.
- (3) *If $a_1 \sim_S a_2$, then $(a_1 \wedge a_2) \setminus_S b = (a_1 \setminus_S b) \wedge (a_2 \setminus_S b)$.*
- (4) *If $b_1 \sim_S b_2$, then $a \setminus_S (b_1 \vee b_2) = (a \setminus_S b_1) \wedge (a \setminus_S b_2)$.*

Proof. Ad (1). For every $s \in S$,

$$\begin{aligned} (a_1 \vee a_2) \setminus_S b \leq s &\Leftrightarrow a_1 \vee a_2 \leq b \vee s \\ &\Leftrightarrow a_1 \leq b \vee s \text{ and } a_2 \leq b \vee s \\ &\Leftrightarrow a_1 \setminus_S b \leq s \text{ and } a_2 \setminus_S b \leq s \\ &\Leftrightarrow (a_1 \setminus_S b) \vee (a_2 \setminus_S b) \leq s. \end{aligned}$$

The desired conclusion follows.

Ad (2). For every $s \in S$,

$$\begin{aligned} a \setminus_S (b_1 \wedge b_2) \leq s &\Leftrightarrow a \leq (b_1 \wedge b_2) \vee s \\ &\Leftrightarrow a \leq b_1 \vee s \text{ and } a \leq b_2 \vee s \quad (\text{because } S \text{ is distributive}) \\ &\Leftrightarrow a \setminus_S b_1 \leq s \text{ and } a \setminus_S b_2 \leq s \\ &\Leftrightarrow (a \setminus_S b_1) \vee (a \setminus_S b_2) \leq s. \end{aligned}$$

The desired conclusion follows.

Ad (3). We first compute as follows:

$$\begin{aligned} a_1 \setminus_S b &\leq (a_1 \setminus_S (a_1 \wedge a_2)) \vee ((a_1 \wedge a_2) \setminus_S b) \quad (\text{use Lemmas 6.4 and 6.7}) \\ &= (a_1 \setminus_S a_2) \vee ((a_1 \wedge a_2) \setminus_S b) \quad (\text{use (D2)}). \end{aligned}$$

Symmetrically, $a_2 \searrow_S b \leq (a_2 \searrow_S a_1) \vee ((a_1 \wedge a_2) \searrow_S b)$. By meeting the two inequalities, we obtain, by using the distributivity of S , the following inequality:

$$(a_1 \searrow_S b) \wedge (a_2 \searrow_S b) \leq ((a_1 \searrow_S a_2) \wedge (a_2 \searrow_S a_1)) \vee ((a_1 \wedge a_2) \searrow_S b).$$

Now our assumption $a_1 \sim_S a_2$ means that $(a_1 \searrow_S a_2) \wedge (a_2 \searrow_S a_1) = 0$, so we obtain the following inequality:

$$(a_1 \searrow_S b) \wedge (a_2 \searrow_S b) \leq (a_1 \wedge a_2) \searrow_S b.$$

The converse inequality is trivial.

Ad (4). We first compute as follows:

$$\begin{aligned} a \searrow_S b_1 &\leq (a \searrow_S (b_1 \vee b_2)) \vee ((b_1 \vee b_2) \searrow_S b_1) && \text{(use Lemmas 6.4 and 6.7)} \\ &= (a \searrow_S (b_1 \vee b_2)) \vee (b_2 \searrow_S b_1) && \text{(use (D2)).} \end{aligned}$$

Symmetrically, $a \searrow_S b_2 \leq (a \searrow_S (b_1 \vee b_2)) \vee (b_1 \searrow_S b_2)$. By meeting the two inequalities, we obtain, by using the distributivity of S , the following inequality:

$$(a \searrow_S b_1) \wedge (a \searrow_S b_2) \leq (a \searrow_S (b_1 \vee b_2)) \vee ((b_1 \searrow_S b_2) \wedge (b_2 \searrow_S b_1)).$$

Now our assumption $b_1 \sim_S b_2$ means that $(b_1 \searrow_S b_2) \wedge (b_2 \searrow_S b_1) = 0$, so we obtain the following inequality:

$$(a \searrow_S b_1) \wedge (a \searrow_S b_2) \leq a \searrow_S (b_1 \vee b_2).$$

The converse inequality is trivial. \square

Lemma 6.9. *Let S be a finite distributive lattice and let $a_1, a_2, b_1, b_2 \in S$. If $a_1 \sim_S a_2$ and $a_1 \wedge a_2 \leq b_1 \wedge b_2$, then $(a_1 \searrow_S b_1) \wedge (a_2 \searrow_S b_2) = 0$.*

Proof. Set $b \stackrel{\text{def}}{=} b_1 \wedge b_2$. We compute as follows:

$$\begin{aligned} (a_1 \searrow_S b_1) \wedge (a_2 \searrow_S b_2) &\leq (a_1 \searrow_S b) \wedge (a_2 \searrow_S b) && \text{(because each } b_i \geq b) \\ &= (a_1 \wedge a_2) \searrow_S b && \text{(use Lemma 6.8)} \\ &= 0 && \text{(by assumption).} \quad \square \end{aligned}$$

Lemma 6.10. *Let D be a consonent sublattice of a finite distributive lattice E , let S be a finite 0-sublattice of a distributive lattice L with zero, let $g: E \rightarrow L$ be a 0-lattice homomorphism such that $g[D]$ is a consonent subset of S . Let G be a subset of D , generating D as a lattice. If $g(x \searrow_E y) \leq g(x) \searrow_S g(y)$ for all $x, y \in G$, then $g(x \searrow_E y) \leq g(x) \searrow_S g(y)$ for all $x, y \in D$.*

The situation in Lemma 6.10 is partly illustrated in Figure 6.3.

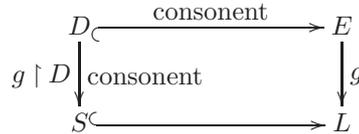


FIGURE 6.3. Illustrating Lemma 6.10

Proof. Let $x \in G$. We claim that the set $D_x \stackrel{\text{def}}{=} \{y \in D \mid g(x \searrow_E y) \leq g(x) \searrow_S g(y)\}$ is equal to D . Indeed, it follows from our assumptions that $G \subseteq D_x$. For all $y_1, y_2 \in D_x$,

$$\begin{aligned}
g(x \searrow_E (y_1 \vee y_2)) &= g((x \searrow_E y_1) \wedge (x \searrow_E y_2)) \\
&\quad \text{(because } D \text{ is consonent in } E \text{ and by Lemma 6.8)} \\
&= g(x \searrow_E y_1) \wedge g(x \searrow_E y_2) \\
&\quad \text{(because } g \text{ is a meet-homomorphism)} \\
&\leq (g(x) \searrow_S g(y_1)) \wedge (g(x) \searrow_S g(y_2)) \quad \text{(because } y_1, y_2 \in D_x) \\
&= g(x) \searrow_S (g(y_1) \vee g(y_2)) \\
&\quad \text{(because } g[D] \text{ is consonent in } S \text{ and by Lemma 6.8)} \\
&= g(x) \searrow_S g(y_1 \vee y_2) \quad \text{(because } g \text{ is a join-homomorphism),}
\end{aligned}$$

that is, $y_1 \vee y_2 \in D_x$. The proof that $y_1 \wedge y_2 \in D_x$ is similar, although easier since it does not require any consonence assumption. Hence, D_x is a sublattice of D . Since it contains G , it contains D ; whence $D_x = D$.

This holds for all $x \in G$, which means that for all $y \in D$, the set $D'_y \stackrel{\text{def}}{=} \{x \in D \mid g(x \searrow_E y) \leq g(x) \searrow_S g(y)\}$ contains G . Moreover, by an argument similar to the one used in the paragraph above, D'_y is a sublattice of D . Hence, $D'_y = D$. This holds for all $y \in D$; the desired conclusion follows. \square

7. HOMOMORPHISM EXTENSION ON DISTRIBUTIVE LATTICES

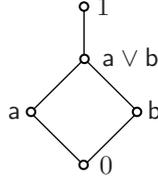
The key idea, of our proof of Theorem 11.1, is the possibility of extending certain lattice homomorphisms $f: D \rightarrow L$, where D and L are distributive 0-lattices with D finite and L completely normal, to finite, or countable, distributive extensions of D . The following example shows that this is hopeless in general.

Example 7.1. Let m be a positive integer, and denote by F_m the Abelian ℓ -group defined by generators a, b, c , and relations $a \geq b \geq c \geq 0$ together with $(a - mb) \vee (b - mc) \leq 0$. Then $0 < \langle c \rangle < \langle b \rangle < \langle a \rangle$ within $\text{Id}_c F_m$, and the 4-element chain $\mathbf{4} \stackrel{\text{def}}{=} \{0, \langle c \rangle, \langle b \rangle, \langle a \rangle\}$ is ℓ -representable (by the third lexicographical power of the integers). We claim that $\mathbf{4}$ is not a lattice-theoretical retract of $\text{Id}_c F_m$. Indeed, suppose that $\rho: \text{Id}_c F_m \rightarrow \mathbf{4}$ is such a retraction, set $\mathbf{x} = \rho((a - mb)^+)$, and $\mathbf{y} = \rho((b - mc)^+)$. Then $\langle a \rangle = \langle b \rangle \vee \mathbf{x}$ within $\mathbf{4}$, thus $\mathbf{x} = \langle a \rangle$. Likewise, $\langle b \rangle = \langle c \rangle \vee \mathbf{y}$, thus $\mathbf{y} = \langle b \rangle$. On the other hand, since ρ is a $(\wedge, 0)$ -homomorphism, $\mathbf{x} \wedge \mathbf{y} = 0$, a contradiction.

The problem raised by Example 7.1 makes our road to Theorem 11.1 more convoluted than one could have expected. The present section contains the required lattice-theoretical extension results.

We will denote by J_2 the second entry of *Jaskowsky's sequence*, defined as the lattice of all lower subsets of the three-element set $\{\mathbf{a}, \mathbf{b}, 1\}$ with $\mathbf{a} < 1$ and $\mathbf{b} < 1$. Hence, J_2 is the distributive lattice obtained from the square, with atoms \mathbf{a} and \mathbf{b} , by adjoining a new top element 1. It is represented in Figure 7.1.

For any bounded distributive lattice D , the free distributive product $D * J_2$, that is, the coproduct of D and J_2 in the category of bounded distributive lattices with 0, 1-lattice homomorphisms, can be identified with the sublattice of D^3 consisting

FIGURE 7.1. The lattice J_2

of all triples $(x, y, z) \in D^3$ such that $z \leq x$ and $z \leq y$. This follows for example from Grätzer [21, Theorem 12.5]. For $x, y, z \in D$, the element $(x \wedge \mathbf{a}) \vee (y \wedge \mathbf{b}) \vee z$ of $D * J_2$ can be identified with the triple $(x \vee z, y \vee z, z)$. We will need the following form of that observation, which no longer requires any boundedness assumption on D and which can be verified by a direct calculation.

Lemma 7.2. *Let D and E be distributive lattices such that E has a zero, and let $a, b \in E$ such that $a \wedge b = 0$. Then for every lattice homomorphism $f: D \rightarrow E$, the map $g: D * J_2 \rightarrow E$ defined by*

$$g(x, y, z) \stackrel{\text{def}}{=} (f(x) \wedge a) \vee (f(y) \wedge b) \vee f(z), \quad \text{for all } (x, y, z) \in D * J_2,$$

is a lattice homomorphism. Moreover, $g(x, x, x) = f(x)$ for every $x \in D$.

The harder extension results in our paper rely upon the following crucial lemma.

Lemma 7.3. *Let E be a finite distributive lattice, let D be a $0, 1$ -sublattice of E , and let $a, b \in E$ such that the following conditions hold:*

- (1) E is generated, as a sublattice, by $D \cup \{a, b\}$.
- (2) D is a Heyting subalgebra of E .
- (3) $a \wedge b = 0$.
- (4) For every $p \in \text{Ji } D$, $p \leq p_* \vee a \vee b$ implies that either $p \leq p_* \vee a$ or $p \leq p_* \vee b$.
- (5) Let $p, q \in \text{Ji } D$. If $p \leq p_* \vee a$ and $q \leq q_* \vee b$, then p and q are incomparable.

Let L be a finite distributive lattice and let $f: D \rightarrow L$ be a consonant 0 -lattice homomorphism. We set

$$\alpha \stackrel{\text{def}}{=} \bigvee (f(p) \searrow_L f(p_*) \mid p \in \text{Ji } D \text{ and } p \leq p_* \vee a),$$

$$\beta \stackrel{\text{def}}{=} \bigvee (f(p) \searrow_L f(p_*) \mid p \in \text{Ji } D \text{ and } p \leq p_* \vee b).$$

Then f extends to a unique lattice homomorphism $g: E \rightarrow L$ such that $g(a) = \alpha$ and $g(b) = \beta$.

Proof. The uniqueness statement on g follows immediately from Assumption (1), so we need to deal only with existence. Our proof consists mainly of a series of claims.

Claim 1. *The following equations hold:*

$$\alpha = \bigvee (f(x) \searrow_L f(y) \mid x, y \in D \text{ and } x \leq y \vee a), \quad (7.1)$$

$$\beta = \bigvee (f(x) \searrow_L f(y) \mid x, y \in D \text{ and } x \leq y \vee b). \quad (7.2)$$

Consequently, $x \leq y \vee a$ implies that $f(x) \leq f(y) \vee \alpha$, and, symmetrically, $x \leq y \vee b$ implies that $f(x) \leq f(y) \vee \beta$, for all $x, y \in D$. Moreover, $\alpha \leq f(1)$ and $\beta \leq f(1)$.

Proof of Claim. Since f is consonant, the assignment $(x, y) \mapsto f(x) \searrow_L f(y)$ defines an L -valued normal difference operation on D (use Lemma 6.7). By Lemma 6.5, it follows that

$$f(x) \searrow_L f(y) = \bigvee (f(p) \searrow_L f(p_*) \mid p \in \text{Ji } D, p \leq x, p \not\leq y), \quad \text{for all } x, y \in D. \quad (7.3)$$

Let $x, y \in D$ such that $x \leq y \vee a$, and let $p \in \text{Ji } D$ such that $p \leq x$ and $p \not\leq y$. The latter relation means that $y \leq p^\dagger$. Hence, from $x \leq y \vee a$ it follows that $p \leq p^\dagger \vee a$, or, equivalently, $p \leq p_* \vee a$. Therefore, by the definition of α , we get $f(p) \searrow_L f(p_*) \leq \alpha$. Joining those inequalities over all possible values of p and invoking (7.3), we get $f(x) \searrow_L f(y) \leq \alpha$. This proves that the right hand side of (7.1) is less than or equal to α . The converse inequality being trivial, (7.1) follows. The proof of (7.2) is symmetric. The final statements, that $\alpha \leq f(1)$ and $\beta \leq f(1)$, are obvious. \square Claim 1.

Claim 2. *Let $x, y \in D$ such that $x \leq y \vee a \vee b$. Then $f(x) \leq f(y) \vee \alpha \vee \beta$.*

Proof of Claim. We must prove that $f(x) \searrow_L f(y) \leq \alpha \vee \beta$. By (7.3), it suffices to prove that $f(p) \searrow_L f(p_*) \leq \alpha \vee \beta$ for every $p \in \text{Ji } D$ such that $p \leq x$ and $p \not\leq y$. The latter relation means that $y \leq p^\dagger$, thus, for any such p , the inequality $p \leq p^\dagger \vee a \vee b$, or, equivalently, $p \leq p_* \vee a \vee b$, holds. By our assumption (4), this implies that either $p \leq p_* \vee a$ or $p \leq p_* \vee b$. By the definition of α and β , this implies that either $f(p) \searrow_L f(p_*) \leq \alpha$ or $f(p) \searrow_L f(p_*) \leq \beta$. Therefore, $f(p) \searrow_L f(p_*) \leq \alpha \vee \beta$. \square Claim 2.

Claim 3. *For every $v \in D$, $a \leq v$ implies that $\alpha \leq f(v)$ and $b \leq v$ implies that $\beta \leq f(v)$.*

Proof of Claim. We prove the first statement; the second statement is symmetric. For every $p \in \text{Ji } D$, $p \leq p_* \vee a$ implies that $p \leq p_* \vee v$ (because $a \leq v$), thus $f(p) \leq f(p_*) \vee f(v)$, that is, $f(p) \searrow_L f(p_*) \leq f(v)$. By joining those inequalities over all possible p , we get $\alpha \leq f(v)$. \square Claim 3.

Claim 4. *There exists a unique map $g: E \rightarrow L$ such that*

$$g((x \wedge a) \vee (y \wedge b) \vee z) = (f(x) \wedge \alpha) \vee (f(y) \wedge \beta) \vee f(z), \quad \text{for all } x, y, z \in D. \quad (7.4)$$

Moreover, $g(a) = \alpha$, $g(b) = \beta$, and g is a join-homomorphism extending f .

Proof of Claim. By our assumptions (1) and (3), every element t of E has the form $(x \wedge a) \vee (y \wedge b) \vee z$, where $x, y, z \in D$. This implies the uniqueness statement on g , and says that all we need to do is to verify that the right hand side of (7.4) depends only on t ; the map g thus defined, *via* (7.4), would then automatically be a join-homomorphism extending f , satisfying, by virtue of the relations $f(0) = 0$, $\alpha \leq f(1)$, and $\beta \leq f(1)$ (cf. Claim 1), the equations $g(a) = \alpha$ and $g(b) = \beta$. Hence, we only need to verify that the following implications hold, for every $u \in D$:

$$u \leq (x \wedge a) \vee (y \wedge b) \vee z \Rightarrow f(u) \leq (f(x) \wedge \alpha) \vee (f(y) \wedge \beta) \vee f(z), \quad (7.5)$$

$$u \wedge a \leq (x \wedge a) \vee (y \wedge b) \vee z \Rightarrow f(u) \wedge \alpha \leq (f(x) \wedge \alpha) \vee (f(y) \wedge \beta) \vee f(z), \quad (7.6)$$

$$u \wedge b \leq (x \wedge a) \vee (y \wedge b) \vee z \Rightarrow f(u) \wedge \beta \leq (f(x) \wedge \alpha) \vee (f(y) \wedge \beta) \vee f(z), \quad (7.7)$$

for all $u, x, y, z \in D$. Since E is distributive, the premise of (7.5) is equivalent to the conjunction of the following inequalities:

$$\begin{aligned} u &\leq x \vee y \vee z; \\ u &\leq x \vee b \vee z; \\ u &\leq a \vee y \vee z; \\ u &\leq a \vee b \vee z. \end{aligned}$$

Since f is a join-homomorphism and by Claims 1 and 2, those inequalities imply the following inequalities:

$$\begin{aligned} f(u) &\leq f(x) \vee f(y) \vee f(z); \\ f(u) &\leq f(x) \vee \beta \vee f(z); \\ f(u) &\leq \alpha \vee f(y) \vee f(z); \\ f(u) &\leq \alpha \vee \beta \vee f(z). \end{aligned}$$

Since L is distributive, this implies in turn that $f(u) \leq (f(x) \wedge \alpha) \vee (f(y) \wedge \beta) \vee f(z)$, thus completing the proof of (7.5).

Similarly, since E is distributive and since $a \wedge b = 0$, the premise of (7.6) is equivalent to the inequality $u \wedge a \leq (x \wedge a) \vee z$, thus to the inequality $u \wedge a \leq x \vee z$, which can be written $a \leq (u \rightarrow_E (x \vee z))$. By Assumption (2), this is equivalent to the inequality $a \leq v$, where we set $v \stackrel{\text{def}}{=} (u \rightarrow_D (x \vee z))$. By Claim 3, this implies that $\alpha \leq f(v)$. Hence, $f(u) \wedge \alpha \leq f(u) \wedge f(v) = f(u \wedge v) \leq f(x \vee z) = f(x) \vee f(z)$. Since L is distributive, this implies in turn that $f(u) \wedge \alpha \leq (f(x) \wedge \alpha) \vee (f(y) \wedge \beta) \vee f(z)$, thus completing the proof of (7.6). The proof of (7.7) is symmetric. \square Claim 4.

Claim 5. $\alpha \wedge \beta = 0$.

Proof of Claim. It suffices to prove that for all $p, q \in \text{Ji } D$ with $p \leq p_* \vee a$ and $q \leq q_* \vee b$, the relation $(f(p) \searrow_L f(p_*)) \wedge (f(q) \searrow_L f(q_*)) = 0$ holds. By Lemma 6.9, it suffices to prove that $f(p) \wedge f(q) \leq f(p_*) \wedge f(q_*)$. Since f is a meet-homomorphism, it suffices to prove that $p \wedge q \leq p_* \wedge q_*$. However, it follows from (5) that p and q are incomparable, so this is obvious. \square Claim 5.

In order to conclude the proof of Lemma 7.3, it is sufficient to prove that g is a meet-homomorphism. By Assumption (3) and Claim 5, respectively, it follows from Lemma 7.2 that there are unique lattice homomorphisms $d: D * \mathbf{J}_2 \rightarrow E$ and $\delta: D * \mathbf{J}_2 \rightarrow L$ such that

$$d(x, y, z) = (x \wedge a) \vee (y \wedge b) \vee z \text{ and } \delta(x, y, z) = (f(x) \wedge \alpha) \vee (f(y) \wedge \beta) \vee f(z)$$

for all $(x, y, z) \in D * \mathbf{J}_2$. Then Claim 4 implies that $\delta = g \circ d$. Moreover, it follows from Assumption (1) that d is surjective. Now any two elements of E have the form $d(t_1)$ and $d(t_2)$, where $t_1, t_2 \in D * \mathbf{J}_2$, and

$$g(d(t_1)) \wedge g(d(t_2)) = \delta(t_1) \wedge \delta(t_2) = \delta(t_1 \wedge t_2) = g(d(t_1 \wedge t_2)) \leq g(d(t_1) \wedge d(t_2)).$$

The converse inequality $g(d(t_1) \wedge d(t_2)) \leq g(d(t_1)) \wedge g(d(t_2))$ is trivial. \square

8. LATTICES OF CONVEX OPEN POLYHEDRAL CONES

Throughout this section we shall fix a real topological vector space \mathbb{E} , not necessarily finite-dimensional. Moreover, in all subsequent sections, for any closed hyperplane H of \mathbb{E} , we shall denote by H^+ and H^- the open half-spaces with boundary H , with associated closed half-spaces $\overline{H}^+ \stackrel{\text{def}}{=} \text{cl}(H^+)$ and $\overline{H}^- \stackrel{\text{def}}{=} \text{cl}(H^-)$.

Notation 8.1. For a set \mathcal{H} of closed hyperplanes of \mathbb{E} , we will set

$$\begin{aligned} \Sigma_{\mathcal{H}} &\stackrel{\text{def}}{=} \{H^+ \mid H \in \mathcal{H}\} \cup \{H^- \mid H \in \mathcal{H}\}, \\ \overline{\Sigma}_{\mathcal{H}} &\stackrel{\text{def}}{=} \{\overline{H}^+ \mid H \in \mathcal{H}\} \cup \{\overline{H}^- \mid H \in \mathcal{H}\}. \end{aligned}$$

Furthermore, we will denote by $\text{Bool}(\mathcal{H})$ the Boolean algebra of subsets of \mathbb{E} generated by $\Sigma_{\mathcal{H}}$ (equivalently, by $\overline{\Sigma}_{\mathcal{H}}$), and by $\text{Clos}(\mathcal{H})$ (resp., $\text{Op}(\mathcal{H})$) the lattice of all closed (resp., open) members of $\text{Bool}(\mathcal{H})$.

In particular, for every $H \in \mathcal{H}$, the hyperplane $H = \mathbb{E} \setminus (H^+ \cup H^-)$ belongs to $\text{Bool}(\mathcal{H})$. Moreover, the bounds of $\text{Bool}(\mathcal{H})$ are \emptyset and \mathbb{E} .

Trivially, $\text{Clos}(\mathcal{H})$ and $\text{Op}(\mathcal{H})$ are both 0, 1-sublattices of $\text{Bool}(\mathcal{H})$, which is a 0, 1-sublattice of the powerset lattice of \mathbb{E} . On one extreme end, $\text{Bool}(\emptyset) = \text{Clos}(\emptyset) = \text{Op}(\emptyset) = \{\emptyset, \mathbb{E}\}$. In general,

$$\begin{aligned} \text{Bool}(\mathcal{H}) &= \bigcup (\text{Bool}(\mathcal{H}') \mid \mathcal{H}' \subseteq \mathcal{H} \text{ finite}), \\ \text{Op}(\mathcal{H}) &= \bigcup (\text{Op}(\mathcal{H}') \mid \mathcal{H}' \subseteq \mathcal{H} \text{ finite}), \\ \text{Clos}(\mathcal{H}) &= \bigcup (\text{Clos}(\mathcal{H}') \mid \mathcal{H}' \subseteq \mathcal{H} \text{ finite}). \end{aligned}$$

For the remainder of this section we shall fix a *nonempty* set \mathcal{H} of closed hyperplanes of \mathbb{E} through the origin.

Lemma 8.2. *For every $X \in \text{Bool}(\mathcal{H})$, the subsets $\text{cl}(X)$ and $\text{int}(X)$ both belong to $\text{Bool}(\mathcal{H})$. Moreover, $\text{Op}(\mathcal{H})$ is generated, as a lattice, by $\Sigma_{\mathcal{H}} \cup \{\mathbb{E}\}$, and it is Heyting subalgebra of the Heyting algebra $\mathcal{O}(\mathbb{E})$ of all open subsets of \mathbb{E} .*

Proof. For the duration of the proof, we shall denote by $\text{Clos}'(\mathcal{H})$ (resp., $\text{Op}'(\mathcal{H})$) the sublattice of $\text{Bool}(\mathcal{H})$ generated by $\overline{\Sigma}_{\mathcal{H}} \cup \{\emptyset\}$ (resp., $\Sigma_{\mathcal{H}} \cup \{\mathbb{E}\}$).

We first prove that the closure of any member of $\text{Bool}(\mathcal{H})$ belongs to $\text{Clos}'(\mathcal{H})$. Writing the elements of $\text{Bool}(\mathcal{H})$ in disjunctive normal form, we see that every element of $\text{Bool}(\mathcal{H})$ is a finite union of finite intersections of open half-spaces and closed half-spaces with boundaries in \mathcal{H} . Since $H^\sigma = \overline{H}^\sigma \setminus H$, for each $H \in \mathcal{H}$ and each $\sigma \in \{+, -\}$, it follows that every element of $\text{Bool}(\mathcal{H})$ is a finite union of sets of the form $Q \setminus F$, where Q is a finite intersection of closed half-spaces with boundaries in \mathcal{H} and F is a finite union of members of \mathcal{H} . Since the closure operator commutes with finite unions, the first statement of Lemma 8.2 thus reduces to verifying that $\text{cl}(Q \setminus F)$ belongs to $\text{Clos}'(\mathcal{H})$, for any Q and F as above. Now this follows from Lemma 2.4: if $Q \subseteq F$ then $\text{cl}(Q \setminus F) = \emptyset$, and if $Q \not\subseteq F$, then $Q \cap F$ is nowhere dense in Q , thus $\text{cl}(Q \setminus F) = \text{cl}(Q) = Q$. The statement about the closure follows; in particular, $\text{Clos}'(\mathcal{H}) = \text{Clos}(\mathcal{H})$. By taking complements, the statement about the interior follows; in particular, $\text{Op}'(\mathcal{H}) = \text{Op}(\mathcal{H})$.

In particular, for all $X, Y \in \text{Op}(\mathcal{H})$, the Heyting residue $X \rightarrow Y$, evaluated within the lattice $\mathcal{O}(\mathbb{E})$ of all open subsets of \mathbb{E} , is equal to $\text{int}((\mathbb{C}X) \cup Y)$, thus, as $(\mathbb{C}X) \cup Y$ belongs to $\text{Bool}(\mathcal{H})$ and by the paragraph above, it belongs to $\text{Op}(\mathcal{H})$. \square

In particular, the members of $\text{Op}(\mathcal{H})$ are *open polyhedral cones*, that is, Boolean combinations of open half-spaces of \mathbb{E} . Lemma 8.2 also says that the topology on \mathbb{E} could be, in principle, omitted from the study of $\text{Bool}(\mathcal{H})$ and $\text{Op}(\mathcal{H})$.

Corollary 8.3. *The subsets $\text{Bool}(\mathcal{H})$ and $\text{Op}(\mathcal{H})$ are independent of the structure of topological vector space on \mathbb{E} that makes all members of \mathcal{H} closed.*

Corollary 8.4. *Let \mathcal{H}_1 and \mathcal{H}_2 be sets of closed hyperplanes of \mathbb{E} . If $\mathcal{H}_1 \subseteq \mathcal{H}_2$, then $\text{Op}(\mathcal{H}_1)$ is a Heyting subalgebra of $\text{Op}(\mathcal{H}_2)$.*

Define a *basic open member* of $\text{Op}(\mathcal{H})$ as a nonempty finite intersection of open half-spaces with boundaries in \mathcal{H} . In particular, the empty intersection yields the basic open set \mathbb{E} .

Corollary 8.5. *Every join-irreducible element of $\text{Op}(\mathcal{H})$ is basic open. In particular, it is convex.*

Proof. It follows from Lemma 8.2 that every element of $\text{Op}(\mathcal{H})$ is a finite union of basic open sets. The desired conclusion follows immediately. \square

It is easy to find examples showing that the converse of Corollary 8.5 does not hold: *A basic open member of $\text{Op}(\mathcal{H})$ may not be join-irreducible.* On the other hand, it can be proved that the basic open members of $\text{Op}(\mathcal{H})$ are exactly its convex members. Since this fact will not be needed in the paper, we omit its proof.

Corollary 8.6. *Let H be a closed hyperplane of \mathbb{E} , with associated open half spaces H^+ and H^- . Then the members of $\text{Op}(\mathcal{H} \cup \{H\})$ are exactly the sets of the form*

$$X \cup (Y^+ \cap H^+) \cup (Y^- \cap H^-), \quad (8.1)$$

where X , Y^+ , and Y^- are basic open in $\text{Op}(\mathcal{H})$. Moreover, one can take $X \subseteq Y^+ \cap Y^-$ in (8.1).

Proof. For every basic open set X in $\text{Op}(\mathcal{H} \cup \{H\})$, there is a basic open set Y in $\text{Op}(\mathcal{H})$ such that either $X = Y$ or $X = Y \cap H^+$ or $X = Y \cap H^-$. By Lemma 8.2, every element of $\text{Op}(\mathcal{H} \cup \{H\})$ is a finite union of basic open sets, thus it has the form (8.1). Moreover, changing Y^σ to $X \cup Y^\sigma$, for $\sigma \in \{+, -\}$, does not affect the right hand side of (8.1). Hence, one can take $X \subseteq Y^+ \cap Y^-$. \square

Lemma 8.7. *The top element of $\text{Op}(\mathcal{H})$, namely \mathbb{E} , is join-irreducible in $\text{Op}(\mathcal{H})$. Consequently, the subset $\text{Op}^-(\mathcal{H}) \stackrel{\text{def}}{=} \text{Op}(\mathcal{H}) \setminus \{\mathbb{E}\}$ is a 0-sublattice of $\text{Op}(\mathcal{H})$. It is generated, as a sublattice, by $\Sigma_{\mathcal{H}}$.*

Proof. Any basic open member of $\text{Op}(\mathcal{H})$, distinct from \mathbb{E} , omits the origin. Hence, any member of $\text{Op}(\mathcal{H})$, distinct from \mathbb{E} , omits the origin, and so the union of any two such sets is distinct from \mathbb{E} . This proves that \mathbb{E} is join-irreducible in $\text{Op}(\mathcal{H})$. The verifications of the other statements of Lemma 8.7 are straightforward. \square

Remark 8.8. Let \mathcal{H} be finite. Then the unit of $\text{Op}^-(\mathcal{H})$ is equal to $\mathbb{E} \setminus \bigcap \mathcal{H}$, which is distinct from the unit of $\text{Op}(\mathcal{H})$, which is equal to \mathbb{E} . In particular, $\text{Op}^-(\mathcal{H})$ is not a Heyting subalgebra of $\text{Op}(\mathcal{H})$.

9. JOIN-IRREDUCIBLE MEMBERS OF $\text{Op}(\mathcal{H})$

Throughout this section we shall fix a real topological vector space \mathbb{E} and a nonempty *finite* set \mathcal{H} of closed hyperplanes of \mathbb{E} through the origin. After having conveniently described the join-irreducible members of $\text{Op}(\mathcal{H})$ (cf. Lemma 9.2), we will specialize Lemma 7.3 to lattices of the form $\text{Op}(\mathcal{H})$.

Notation 9.1. For every $U \in \text{Op}(\mathcal{H})$, we set $\mathcal{H}_U \stackrel{\text{def}}{=} \{H \in \mathcal{H} \mid H \cap U \neq \emptyset\}$. The intersection ∇U of all members of \mathcal{H}_U is a closed subspace of \mathbb{E} .

The following lemma characterizes the join-irreducible elements in $\text{Op}(\mathcal{H})$ in terms of the operator ∇ defined above. Recall (cf. Lemma 2.1) that P^\dagger denotes the largest element of $\text{Op}(\mathcal{H})$ not containing P , and that the assignment $P \mapsto P^\dagger$ defines an order-isomorphism from $\text{Ji Op}(\mathcal{H})$ onto $\text{Mi Op}(\mathcal{H})$.

Lemma 9.2. *A nonempty, convex member P of $\text{Op}(\mathcal{H})$ is join-irreducible, within the lattice $\text{Op}(\mathcal{H})$, iff $P \cap \nabla P$ is nonempty. Moreover, in that case, the lower cover P_* of P , in $\text{Op}(\mathcal{H})$, is equal to $P \setminus \nabla P$, and $P^\dagger = \mathbb{E} \setminus (\text{cl}(P) \cap \nabla P)$.*

Proof. Suppose first that P is join-irreducible. Suppose, by way of contradiction, that $P \cap \nabla P = \emptyset$, that is, $P \subseteq \bigcup_{H \in \mathcal{H}_P} (\mathbb{E} \setminus H)$. Since P is join-irreducible in the distributive lattice $\text{Op}(\mathcal{H})$, it is join-prime in that lattice (cf. Lemma 2.1). Since each $\mathbb{E} \setminus H$ belongs to $\text{Op}(\mathcal{H})$, there exists $H \in \mathcal{H}_P$ such that $P \subseteq \mathbb{E} \setminus H$; in contradiction with $H \in \mathcal{H}_P$.

Suppose, conversely, that $P \cap \nabla P \neq \emptyset$. The subset $P \setminus \nabla P$ belongs to $\text{Op}(\mathcal{H})$ and it is a proper subset of P , thus we only need to prove that every proper subset X of P , belonging to $\text{Op}(\mathcal{H})$, is contained in $P \setminus \nabla P$. It suffices to consider the case where X is join-irreducible in $\text{Op}(\mathcal{H})$. By Corollary 8.5, X is basic open, so there are a subset \mathcal{X} of \mathcal{H} and a family $(\varepsilon_H \mid H \in \mathcal{X})$ of elements of $\{+, -\}$ such that $X = \bigcap_{H \in \mathcal{X}} H^{\varepsilon_H}$. Since $P \not\subseteq X$, there exists $H \in \mathcal{X}$ such that $P \not\subseteq H^{\varepsilon_H}$. Hence,

$$P \cap \overline{H}^{-\varepsilon_H} \neq \emptyset. \quad (9.1)$$

If $P \subseteq H^{-\varepsilon_H}$, then $X \subseteq H^{-\varepsilon_H}$, thus, since $X \subseteq H^{\varepsilon_H}$, we get $X = \emptyset$, a contradiction since X is join-irreducible. Hence, $P \not\subseteq H^{-\varepsilon_H}$, so

$$P \cap \overline{H}^{\varepsilon_H} \neq \emptyset. \quad (9.2)$$

By (9.1) and (9.2), and since P is convex, it follows that $P \cap H \neq \emptyset$, that is, $H \in \mathcal{H}_P$. Hence, $\nabla P \subseteq H$. Since $X \cap H = \emptyset$, it follows that $X \cap \nabla P = \emptyset$, thus completing the proof of the join-irreducibility of P .

Finally, it follows from Lemma 8.2 that the set $U \stackrel{\text{def}}{=} \text{int } \mathcal{C}(P \cap \nabla P)$ belongs to $\text{Op}(\mathcal{H})$. Moreover, $U = \mathcal{C} \text{cl}(P \cap \nabla P)$. Since $P \cap \nabla P \neq \emptyset$ and by Lemma 2.3, we get $U = \mathcal{C}(\text{cl}(P) \cap \nabla P)$. For every $V \in \text{Op}(\mathcal{H})$, $P \not\subseteq V$ iff $P \cap V \subsetneq P$, iff $P \cap V \subseteq P_*$, iff $P \cap V \cap \nabla P = \emptyset$, iff $V \subseteq \mathcal{C}(P \cap \nabla P)$. Since V is open, this is equivalent to $V \subseteq U$. Therefore, $U = P^\dagger$. \square

Note. The *atoms* of $\text{Op}(\mathcal{H})$, called the *regions* of the hyperplane arrangement \mathcal{H} , have been studied extensively, starting with Björner, Edelman, and Ziegler [6]. For an atom P of $\text{Op}(\mathcal{H})$, we get $\mathcal{H}_P = \emptyset$, thus $\nabla P = \mathbb{E}$.

Proposition 9.3. *Let P and Q be join-irreducible elements in $\text{Op}(\mathcal{H})$. If $P \subsetneq Q$, then $\nabla Q \subsetneq \nabla P$.*

Proof. By definition, $\mathcal{H}_P \subseteq \mathcal{H}_Q$, thus $\nabla Q \subseteq \nabla P$. Since $P \subsetneq Q$ and by Lemma 9.2, P is contained in $Q_* = Q \setminus \nabla Q$, thus $P \cap \nabla Q = \emptyset$. Since $P \cap \nabla P \neq \emptyset$, it follows that $\nabla P \neq \nabla Q$. \square

Lemma 9.4. *Let H be a closed hyperplane of \mathbb{E} , let L be a finite distributive lattice, and let $f: \text{Op}(\mathcal{H}) \rightarrow L$ be a consonant 0-lattice homomorphism. We set*

$$\gamma^\sigma \stackrel{\text{def}}{=} \bigvee (f(P) \searrow_L f(P_*) \mid P \in \text{Ji Op}(\mathcal{H}), P \subseteq P_* \cup H^\sigma), \quad \text{for each } \sigma \in \{+, -\}.$$

Then f extends to a unique lattice homomorphism $g: \text{Op}(\mathcal{H} \cup \{H\}) \rightarrow L$ such that $g(H^+) = \gamma^+$ and $g(H^-) = \gamma^-$.

Proof. We verify that Conditions (1)–(5) of Lemma 7.3 are satisfied, where we set $D \stackrel{\text{def}}{=} \text{Op}(\mathcal{H})$, $E \stackrel{\text{def}}{=} \text{Op}(\mathcal{H} \cup \{H\})$, $a \stackrel{\text{def}}{=} H^+$, and $b \stackrel{\text{def}}{=} H^-$. Conditions (1) (use Corollary 8.6) and (3) are obvious. By Corollary 8.4, $\text{Op}(\mathcal{H})$ is a Heyting subalgebra of $\text{Op}(\mathcal{H} \cup \{H\})$; Condition (2) follows.

Let P be a join-irreducible element of $\text{Op}(\mathcal{H})$ such that $P \subseteq P_* \cup H^+ \cup H^-$. By Lemma 9.2, this means that $P \cap \nabla P \subseteq H^+ \cup H^-$. Since $P \cap \nabla P$ is convex, this implies that $P \cap \nabla P$ is contained either in H^+ or in H^- , thus that P is contained either in $P_* \cup H^+$ or in $P_* \cup H^-$. Condition (4) follows.

For Condition (5), let $P, Q \in \text{Ji Op}(\mathcal{H})$ such that $P \subseteq P_* \cup H^+$ and $Q \subseteq Q_* \cup H^-$. Suppose that $P \subseteq Q$. This means that $P \cap \nabla P \subseteq H^+$, $Q \cap \nabla Q \subseteq H^-$, and $P^\dagger \subseteq Q^\dagger$, thus, by Lemma 9.2, $\text{cl}(Q) \cap \nabla Q \subseteq \text{cl}(P) \cap \nabla P$. Hence, $Q \cap \nabla Q \subseteq \overline{H^+}$, and hence $Q \cap \nabla Q = \emptyset$, a contradiction. If $Q \subseteq P$, we get a similar contradiction. \square

10. EXTENDING HOMOMORPHISMS ON OPEN POLYHEDRAL CONES

Throughout this section we will consider the free real vector space $\mathbb{R}^{(\omega)}$ on ω (see Section 3 for the notation). We endow $\mathbb{R}^{(\omega)}$ with its canonical inner product, defined by

$$(x|y) \stackrel{\text{def}}{=} \sum_{n \in \omega} x_n y_n, \quad \text{for all } x, y \in \mathbb{R}^{(\omega)}.$$

This enables us to identify every element $x \in \mathbb{R}^{(\omega)}$ with the linear functional $(x|_)$. We endow $\mathbb{R}^{(\omega)}$ with its *weak topology*, making all those linear functionals continuous. A hyperplane H of $\mathbb{R}^{(\omega)}$ is closed iff it is the kernel of some element of $\mathbb{R}^{(\omega)} \setminus \{0\}$. Since x is determined up to a scalar multiple, the support of x depends on H only, so we will denote it by $\text{supp}(H)$. An element $x \in \mathbb{R}^{(\omega)}$ is *integral* if all its entries are integers, that is, $x \in \mathbb{Z}^{(\omega)}$, and we say that a hyperplane H of $\mathbb{R}^{(\omega)}$ is *integral* if it is the kernel of some element of $\mathbb{Z}^{(\omega)} \setminus \{0\}$. For a set \mathcal{H} of closed hyperplanes of $\mathbb{R}^{(\omega)}$, we shall set $\text{supp}(\mathcal{H}) \stackrel{\text{def}}{=} \bigcup (\text{supp}(H) \mid H \in \mathcal{H})$.

For any $n \in \omega$, we shall denote by δ_n the vector whose n th coordinate is 1 and all other coordinates are 0, and we shall denote by Δ_n the kernel of δ_n , that is, $\Delta_n \stackrel{\text{def}}{=} \{x \in \mathbb{R}^{(\omega)} \mid x_n = 0\}$. We shall also set

$$\Delta_n^+ \stackrel{\text{def}}{=} \{x \in \mathbb{R}^{(\omega)} \mid x_n > 0\}, \quad \Delta_n^- \stackrel{\text{def}}{=} \{x \in \mathbb{R}^{(\omega)} \mid x_n < 0\}.$$

For $x \in \mathbb{R}^{(\omega)}$ and $S \subseteq \omega$, we shall denote by $x|_S$ the restriction of x to S , extended by zero on $\omega \setminus S$.

Lemma 10.1. *Let \mathcal{H} be a set of closed hyperplanes of $\mathbb{R}^{(\omega)}$, with support S , and let $Z \in \text{Bool}(\mathcal{H})$. Then $x \in Z$ iff $x|_S \in Z$, for all $x \in \mathbb{R}^{(\omega)}$.*

Proof. For each $H \in \mathcal{H}$, pick a vector $p_H \in \mathbb{R}^{(\omega)}$ with kernel H , and set $H^+ \stackrel{\text{def}}{=} \llbracket p_H > 0 \rrbracket$, $H^- \stackrel{\text{def}}{=} \llbracket p_H < 0 \rrbracket$. Then for every $x \in \mathbb{R}^{(\omega)}$, $x \in H^+$ iff $(p_H|x) > 0$, iff $(p_H|x|_S) > 0$, iff $x|_S \in H^+$. The proof for H^- is similar. Since the H^+ and the H^- generate $\text{Bool}(\mathcal{H})$ as a Boolean algebra, the general result follows easily. \square

Our next two lemmas both involve the construction $D*\mathbb{J}_2$ introduced in Section 7.

Lemma 10.2. *Let \mathcal{H} be a set of closed hyperplanes of $\mathbb{R}^{(\omega)}$ and let $n \in \omega \setminus \text{supp}(\mathcal{H})$. We denote by $\varphi: \text{Op}(\mathcal{H}) \hookrightarrow \text{Op}(\mathcal{H}) * \mathbb{J}_2$ the diagonal embedding, by $\psi: \text{Op}(\mathcal{H}) \hookrightarrow \text{Op}(\mathcal{H} \cup \{\Delta_n\})$ the inclusion map, and we set $\varepsilon(X, Y, Z) \stackrel{\text{def}}{=} (X \cap \Delta_n^+) \cup (Y \cap \Delta_n^-) \cup Z$, for all $(X, Y, Z) \in \text{Op}(\mathcal{H}) * \mathbb{J}_2$. Then ε is an isomorphism, and $\psi = \varepsilon \circ \varphi$.*

We illustrate Lemma 10.2 on Figure 10.1.

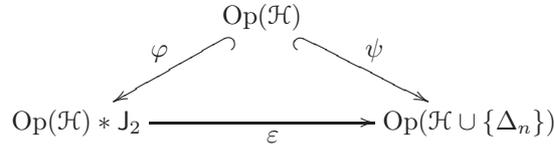


FIGURE 10.1. Illustrating Lemma 10.2

Proof. It is straightforward to verify that φ and ψ are both 0, 1-lattice homomorphisms, that ε is a 0, 1-join-homomorphism, and that $\psi = \varepsilon \circ \varphi$. Moreover, it follows from Corollary 8.6 that ε is surjective.

Set $S \stackrel{\text{def}}{=} \text{supp}(\mathcal{H})$. In order to prove that ε is one-to-one, it is sufficient to prove that every triple $(X, Y, Z) \in \text{Op}(\mathcal{H}) * \mathbb{J}_2$ is determined by the set $T \stackrel{\text{def}}{=} \varepsilon(X, Y, Z)$. Let $t \in \mathbb{R}^{(\omega)}$. Then $t|_S \in \Delta_n$, thus $t|_S \in T$ iff $t|_S \in Z$, iff $t \in Z$ (cf. Lemma 10.1); hence T determines Z . Likewise, $t|_{S+\delta_n} \in \Delta_n^+$, thus $t|_{S+\delta_n} \in T$ iff $t|_{S+\delta_n}$ belongs to $X \cup Z = X$, iff (using again Lemma 10.1) $t|_S \in X$, iff $t \in X$. Symmetrically, $t|_{S-\delta_n} \in T$ iff $t \in Y$. Therefore, T determines both X and Y . \square

Lemma 10.3. *Let \mathcal{H} be a set of closed hyperplanes and let $n \in \omega \setminus \text{supp}(\mathcal{H})$. Let L be a bounded distributive lattice, and let $a, b \in L$ such that $a \wedge b = 0$. Then every 0, 1-lattice homomorphism $f: \text{Op}(\mathcal{H}) \rightarrow L$ extends to a unique 0, 1-lattice homomorphism $g: \text{Op}(\mathcal{H} \cup \{\Delta_n\}) \rightarrow L$ such that $a = g(\Delta_n^+)$ and $b = g(\Delta_n^-)$.*

Proof. By Lemma 10.2, Lemma 10.3 can be reformulated, by replacing $\text{Op}(\mathcal{H} \cup \{\Delta_n\})$ by $\text{Op}(\mathcal{H}) * \mathbb{J}_2$, the inclusion map $\psi: \text{Op}(\mathcal{H}) \hookrightarrow \text{Op}(\mathcal{H} \cup \{\Delta_n\})$ by the canonical embedding $\varphi: \text{Op}(\mathcal{H}) \hookrightarrow \text{Op}(\mathcal{H}) * \mathbb{J}_2$, Δ_n^+ by $\varepsilon^{-1}(\Delta_n^+) = (\mathbb{E}, \emptyset, \emptyset)$, and Δ_n^- by $\varepsilon^{-1}(\Delta_n^-) = (\emptyset, \mathbb{E}, \emptyset)$.

By Lemma 7.2, the map $g: \text{Op}(\mathcal{H}) * \mathbb{J}_2 \rightarrow L$ defined by

$$g(X, Y, Z) \stackrel{\text{def}}{=} (f(X) \wedge a) \vee (f(Y) \wedge b) \vee f(Z), \quad \text{for all } (X, Y, Z) \in \text{Op}(\mathcal{H}) * \mathbb{J}_2,$$

is a lattice homomorphism, and $g(X, X, X) = f(X)$ for every $X \in \text{Op}(\mathcal{H})$. The latter condition means that $f = g \circ \varphi$. Now $a = g(\mathbb{E}, \emptyset, \emptyset)$ and $b = g(\emptyset, \mathbb{E}, \emptyset)$. \square

Lemma 10.4. *Let \mathcal{H} be a finite set of closed hyperplanes of $\mathbb{R}^{(\omega)}$, let $a, b \in \mathbb{R}^{(\omega)}$ with respective kernels A and B , both belonging to \mathcal{H} . We set*

$$\begin{aligned} A^+ &\stackrel{\text{def}}{=} \llbracket a > 0 \rrbracket, & A^- &\stackrel{\text{def}}{=} \llbracket a < 0 \rrbracket, \\ B^+ &\stackrel{\text{def}}{=} \llbracket b > 0 \rrbracket, & B^- &\stackrel{\text{def}}{=} \llbracket b < 0 \rrbracket, \\ C_m &\stackrel{\text{def}}{=} \ker(a - mb), & \mathcal{H}_m &\stackrel{\text{def}}{=} \mathcal{H} \cup \{C_m\}, \\ C_m^+ &\stackrel{\text{def}}{=} \llbracket a > mb \rrbracket, & C_m^- &\stackrel{\text{def}}{=} \llbracket a < mb \rrbracket, \end{aligned}$$

for any positive integer m . Then for all large enough m , the following statement holds: For every finite distributive lattice L , every consonent 0-lattice homomorphism $f: \text{Op}(\mathcal{H}) \rightarrow L$ extends to a lattice homomorphism $g: \text{Op}(\mathcal{H}_m) \rightarrow L$ such that $g(A^+ \setminus_{\text{Op}^-(\mathcal{H}_m)} B^+) = f(A^+) \setminus_L f(B^+)$.

Note. The notation $A^+ \setminus_{\text{Op}^-(\mathcal{H}_m)} B^+$ might look a bit crowded, in particular due to the use of $\text{Op}^-(\mathcal{H}_m)$ instead of $\text{Op}(\mathcal{H}_m)$. In reality, the distinction is immaterial here, because $\text{Op}^-(\mathcal{H}_m)$ is an ideal of $\text{Op}(\mathcal{H}_m)$, thus $U \setminus_{\text{Op}^-(\mathcal{H}_m)} V = U \setminus_{\text{Op}(\mathcal{H}_m)} V$ for all $U, V \in \text{Op}^-(\mathcal{H}_m)$.

Proof. Every $P \in \text{Ji Op}(\mathcal{H})$ is basic open, thus both $\text{cl}(P)$ and ∇P are intersections of closed half-spaces with boundaries in \mathcal{H} . Hence, there is a finite subset Φ_P of $\mathbb{R}^{(\omega)} \setminus \{0\}$ such that $\text{cl}(P) \cap \nabla P = \bigcap_{x \in \Phi_P} \llbracket x \geq 0 \rrbracket$ and $\ker(x) \in \mathcal{H}$ for every $x \in \Phi_P$. Denote by K_P the convex cone of $\mathbb{R}^{(\omega)}$ generated by Φ_P . We set

$$\mathcal{P} \stackrel{\text{def}}{=} \{P \in \text{Ji Op}(\mathcal{H}) \mid -b \notin K_P\}.$$

Since K_P is a finitely generated convex cone of $\mathbb{R}^{(\omega)}$, it has the form

$$\bigcap_{i=1}^k \llbracket p_i \geq 0 \rrbracket \cap \bigcap_{l \geq m} \Delta_l,$$

for nonzero vectors $p_i \in \mathbb{R}^{(\omega)}$ and some $m \in \omega$ (cf. De Loera, Hemmecke, and Köppe [13, Section 1.2]; the $\bigcap_{l \geq m} \Delta_l$ is put there in order to reduce the problem to the finite-dimensional case). Hence K_P is topologically closed, and hence there exists a positive integer m_0 such that

$$-b + (1/m)a \notin K_P, \text{ for all } P \in \mathcal{P} \text{ and all } m \geq m_0. \quad (10.1)$$

We shall prove that every integer $m \geq m_0$ has the property stated in Lemma 10.4. Let L be a finite distributive lattice and let $f: \text{Op}(\mathcal{H}) \rightarrow L$ be a consonent 0-lattice homomorphism. We consider the extension g of f , to a homomorphism from $\text{Op}(\mathcal{H}_m)$ to L , given by Lemma 9.4, with $H := C_m$. In particular,

$$g(C_m^+) = \bigvee (f(P) \setminus_L f(P_*)) \mid P \in \text{Ji Op}(\mathcal{H}), P \subseteq P_* \cup C_m^+. \quad (10.2)$$

We claim that the following inequality holds:

$$f(A^+) \wedge g(C_m^+) \leq f(A^+) \setminus_L f(B^+). \quad (10.3)$$

Since L is distributive, this amounts to proving the following statement.

$$\begin{aligned} f(A^+) \wedge (f(P) \setminus_L f(P_*)) &\leq f(A^+) \setminus_L f(B^+), \\ &\text{for every } P \in \text{Ji Op}(\mathcal{H}) \text{ such that } P \subseteq P_* \cup C_m^+. \end{aligned} \quad (10.4)$$

Let $P \in \text{Ji Op}(\mathcal{H})$ such that $P \subseteq P_* \cup C_m^+$; that is, $P \cap \nabla P \subseteq C_m^+$.

Claim 1. $\text{cl}(P) \cap \nabla P \subseteq \overline{B}^-$.

Proof of Claim. By Lemma 2.2, the statement $\text{cl}(P) \cap \nabla P \subseteq \overline{B}^-$ is equivalent to the relation $-b \in K_P$, that is, $P \notin \mathcal{P}$. Suppose, to the contrary, that $P \in \mathcal{P}$. Then, by (10.1), we get $-b + (1/m)a \notin K_P$. Again by Lemma 2.2, this means that $\text{cl}(P) \cap \nabla P \not\subseteq \llbracket a \geq mb \rrbracket$. On the other hand, the assumption $P \subseteq P_* \cup C_m^+$ means that $P \cap \nabla P \subseteq \llbracket a > mb \rrbracket$, which implies (cf. Lemma 2.3) that $\text{cl}(P) \cap \nabla P \subseteq \llbracket a \geq mb \rrbracket$; a contradiction. \square Claim 1.

Claim 2. $P \cap B^+ \subseteq P_*$.

Proof of Claim. Otherwise $P \subseteq B^+$, thus, *a fortiori*, $P \cap \nabla P \subseteq B^+$. By Claim 1, it follows that $P \cap \nabla P \subseteq B^+ \cap \overline{B}^- = \emptyset$, a contradiction. \square Claim 2.

Now suppose that $P \subseteq A^+$. By Claim 2, the inequalities $P \subseteq P_* \cup A^+$ and $P \cap B^+ \subseteq P_*$ both hold, thus also $f(P) \leq f(P_*) \vee f(A^+)$ and $f(P) \wedge f(B^+) \leq f(P_*)$. Since \searrow_L is a difference operation on the range of f , it follows from Lemma 6.6 that $f(P) \searrow_L f(P_*) \leq f(A^+) \searrow_L f(B^+)$, which implies (10.4) right away.

It remains to handle the case where $P \not\subseteq A^+$. Due to the obvious containment $C_m^+ \subseteq A^+ \cup B^-$, we get $P \subseteq P_* \cup A^+ \cup B^-$, thus, since P is join-prime in $\text{Op}(\mathcal{H})$, we get $P \subseteq B^-$, thus $P \cap B^+ = \emptyset$, and thus $f(P) \wedge f(B^+) = 0$. Now suppose that (10.4) fails, and let $q \in \text{Ji}L$ below the left hand side but not the right hand side. Since $q \leq f(A^+) \leq f(B^+) \vee (f(A^+) \searrow_L f(B^+))$ and $q \not\leq f(A^+) \searrow_L f(B^+)$, we get $q \leq f(B^+)$. But $q \leq f(P) \searrow_L f(P_*) \leq f(P)$, thus $q \leq f(B^+) \wedge f(P) = 0$, a contradiction. This completes the proof of (10.4) in the general case, and therefore of (10.3).

Now obviously, $A^+ \subseteq B^+ \cup (A^+ \cap C_m^+)$, thus $A^+ \searrow_{\text{Op}^-(\mathcal{H}_m)} B^+ \subseteq A^+ \cap C_m^+$, and thus

$$g(A^+ \searrow_{\text{Op}^-(\mathcal{H}_m)} B^+) \leq g(A^+ \cap C_m^+) = f(A^+) \wedge g(C_m^+) \leq f(A^+) \searrow_L f(B^+).$$

Since $f(A^+) \leq f(B^+) \vee g(A^+ \searrow_{\text{Op}^-(\mathcal{H}_m)} B^+)$, the converse inequality

$$f(A^+) \searrow_L f(B^+) \leq g(A^+ \searrow_{\text{Op}^-(\mathcal{H}_m)} B^+)$$

holds, and therefore $f(A^+) \searrow_L f(B^+) = g(A^+ \searrow_{\text{Op}^-(\mathcal{H}_m)} B^+)$. \square

Notation 10.5. We set

$$\mathcal{H}_\Phi \stackrel{\text{def}}{=} \{\ker(x) \mid x \in \Phi\}, \quad \text{for every } \Phi \subseteq \mathbb{R}^{(\omega)} \setminus \{0\}.$$

Say that a subset Φ of $\mathbb{R}^{(\omega)}$ is *symmetric* if $-\Phi = \Phi$.

Lemma 10.6. Let Φ be a symmetric subset of $\mathbb{R}^{(\omega)} \setminus \{0\}$ and set

$$\Phi^+ \stackrel{\text{def}}{=} \Phi \cup \{x - y \mid x, y \in \Phi \text{ and } x \neq y\}.$$

Then Φ^+ is symmetric and $\text{Op}^-(\mathcal{H}_\Phi)$ is consonant in $\text{Op}^-(\mathcal{H}_{\Phi^+})$.

Proof. It is trivial that Φ^+ is symmetric. Since $\text{Op}^-(\mathcal{H}_\Phi)$ is generated, as a lattice, by $\Sigma_{\mathcal{H}_\Phi}$ (cf. Lemma 8.7), it suffices, by Lemma 6.2, to prove that for any distinct $A, B \in \mathcal{H}_\Phi$, any two open half-spaces A^+ and B^+ , with respective boundaries A and B , are consonant in $\text{Op}^-(\mathcal{H}_{\Phi^+})$. Since Φ is symmetric, there are $a, b \in \Phi$, with respective kernels A and B , such that $A^+ = \llbracket a > 0 \rrbracket$ and $B^+ = \llbracket b > 0 \rrbracket$. The vectors $a - b$ and $b - a$ both belong to Φ^+ , with $A^+ \subseteq B^+ \cup \llbracket a - b > 0 \rrbracket$,

$B^+ \subseteq A^+ \cup \llbracket b - a > 0 \rrbracket$, and $\llbracket a - b > 0 \rrbracket \cap \llbracket b - a > 0 \rrbracket = \emptyset$. Hence, A^+ and B^+ are consonent in $\text{Op}^-(\mathcal{H}_{\Phi^+})$. \square

Lemma 10.7. *Let \mathcal{H} be a finite set of integral hyperplanes, let L be a completely normal distributive lattice with zero, let $f: \text{Op}(\mathcal{H}) \rightarrow L$ be a 0-lattice homomorphism, let $U, V \in \text{Op}^-(\mathcal{H})$, and let $\gamma \in L$ such that $f(U) \leq f(V) \vee \gamma$. Then there are a finite set $\tilde{\mathcal{H}}$ of integral hyperplanes, containing \mathcal{H} , and a lattice homomorphism $g: \text{Op}(\tilde{\mathcal{H}}) \rightarrow L$ extending f , such that the following statements hold:*

- (1) $\text{Op}^-(\tilde{\mathcal{H}})$ is consonent in $\text{Op}^-(\tilde{\mathcal{H}})$.
- (2) There exists $W \in \text{Op}^-(\tilde{\mathcal{H}})$ such that $U \subseteq V \cup W$ and $g(W) \leq \gamma$.

Proof. We may assume that \mathcal{H} is nonempty. Fix an enumeration $(A_0, B_0), \dots, (A_{n-1}, B_{n-1})$ of all pairs of open half-spaces with boundary in \mathcal{H} . Moreover, fix a finite chain $S_0 \subseteq S_1 \subseteq \dots \subseteq S_n$ of finite sublattices of L , such that S_0 contains $f[\text{Op}(\mathcal{H})] \cup \{\gamma\}$ and S_i is consonent in S_{i+1} whenever $0 \leq i < n$. We construct inductively an ascending chain $\mathcal{H} = \mathcal{H}_0 \subseteq \mathcal{H}_1 \subseteq \dots \subseteq \mathcal{H}_n$ of finite sets of integral hyperplanes, together with an ascending chain of lattice homomorphisms $f_l: \text{Op}(\mathcal{H}_l) \rightarrow S_l$, for $0 \leq l \leq n$, such that $f_0 = f$ and

$$f_k(A_l \setminus_{\text{Op}^-(\mathcal{H}_k)} B_l) \leq f(A_l) \setminus_{S_1} f(B_l), \quad \text{whenever } 0 \leq l < k \leq n. \quad (10.5)$$

For $k = 0$ there is nothing to verify. Suppose having performed the construction up to level k , with $0 \leq k < n$. By applying Lemma 10.4, with \mathcal{H}_k in place of \mathcal{H} , f_k in place of f , S_{k+1} in place of L , and (A_k, B_k) in place of (A^+, B^+) , we get a finite set \mathcal{H}_{k+1} of integral hyperplanes, containing \mathcal{H}_k , together with a lattice homomorphism $f_{k+1}: \text{Op}(\mathcal{H}_{k+1}) \rightarrow S_{k+1}$, extending f_k , such that

$$f_{k+1}(A_k \setminus_{\text{Op}^-(\mathcal{H}_{k+1})} B_k) = f(A_k) \setminus_{S_{k+1}} f(B_k).$$

Since S_{k+1} contains S_1 , it follows that

$$f_{k+1}(A_k \setminus_{\text{Op}^-(\mathcal{H}_{k+1})} B_k) \leq f(A_k) \setminus_{S_1} f(B_k). \quad (10.6)$$

Since $\text{Op}^-(\mathcal{H}_k)$ is a sublattice of $\text{Op}^-(\mathcal{H}_{k+1})$ and since f_{k+1} extends f_k , it follows from the induction hypothesis (10.5) (with fixed k) that

$$f_{k+1}(A_l \setminus_{\text{Op}^-(\mathcal{H}_{k+1})} B_l) \leq f(A_l) \setminus_{S_1} f(B_l), \quad \text{whenever } 0 \leq l < k,$$

and hence, by (10.6),

$$f_{k+1}(A_l \setminus_{\text{Op}^-(\mathcal{H}_{k+1})} B_l) \leq f(A_l) \setminus_{S_1} f(B_l), \quad \text{whenever } 0 \leq l < k + 1,$$

thus completing the verification of the induction step.

At stage n , we obtain a finite set \mathcal{H}_n of integral hyperplanes, containing \mathcal{H} , together with a homomorphism $f_n: \text{Op}(\mathcal{H}_n) \rightarrow S_n$, extending f , such that

$$f_n(A_k \setminus_{\text{Op}^-(\mathcal{H}_n)} B_k) \leq f(A_k) \setminus_{S_1} f(B_k), \quad \text{whenever } 0 \leq k < n. \quad (10.7)$$

By Lemma 10.6, there is a finite set $\tilde{\mathcal{H}}$ of integral hyperplanes, containing \mathcal{H}_n , such that $\text{Op}(\mathcal{H}_n)$ (thus, *a fortiori*, $\text{Op}(\mathcal{H})$) is consonent in $\text{Op}(\tilde{\mathcal{H}})$. Moreover, by Lemma 9.4, the homomorphism $f_n: \text{Op}(\mathcal{H}_n) \rightarrow S_n$ extends to a homomorphism $g: \text{Op}(\tilde{\mathcal{H}}) \rightarrow \tilde{S}$ for some finite sublattice \tilde{S} of L containing S_n . Hence, from (10.7) it follows that

$$g(A_k \setminus_{\text{Op}^-(\tilde{\mathcal{H}})} B_k) \leq f(A_k) \setminus_{S_1} f(B_k), \quad \text{whenever } 0 \leq k < n. \quad (10.8)$$

Since the open half-spaces, with boundary in \mathcal{H} , generate $\text{Op}^-(\mathcal{H})$ as a lattice

$$\begin{array}{ccc}
\text{Op}^-(\mathcal{H}) & \xrightarrow{\text{consonent}} & \text{Op}^-(\tilde{\mathcal{H}}) \\
f \upharpoonright_{\text{Op}^-(\mathcal{H})} = g \upharpoonright_{\text{Op}^-(\mathcal{H})} \downarrow & \text{consonent} & \downarrow g \upharpoonright_{\text{Op}^-(\tilde{\mathcal{H}})} \\
S_1 \subset & \xrightarrow{\quad} & \tilde{S}
\end{array}$$

FIGURE 10.2. Illustrating the proof of Lemma 10.7

(cf. Lemma 8.7) and since every pair of such half-spaces has the form (A_k, B_k) , it follows from Lemma 6.10, applied to (10.8) and the commutative square represented in Figure 10.2, that

$$g(X \setminus_{\text{Op}^-(\tilde{\mathcal{H}})} Y) \leq f(X) \setminus_{S_1} f(Y), \quad \text{for all } X, Y \in \text{Op}^-(\mathcal{H}).$$

In particular, $g(U \setminus_{\text{Op}^-(\tilde{\mathcal{H}})} V) \leq f(U) \setminus_{S_1} f(V) \leq \gamma$. Let $W \stackrel{\text{def}}{=} U \setminus_{\text{Op}^-(\tilde{\mathcal{H}})} V$. \square

Lemma 10.8. *Let \mathcal{H} be a finite set of integral hyperplanes, let L be a completely normal distributive lattice with zero, let $f: \text{Op}(\mathcal{H}) \rightarrow L$ be a 0-lattice homomorphism, let n be a positive integer, and let $\{(U_i, V_i, \gamma_i) \mid i \in [n]\}$ be a set of triples of elements of $\text{Op}^-(\mathcal{H})^2 \times L$ such that $f(U_i) \leq f(V_i) \vee \gamma_i$ for each $i \in [n]$. Then there are a finite set $\tilde{\mathcal{H}}$ of integral hyperplanes, containing \mathcal{H} , and a lattice homomorphism $g: \text{Op}(\tilde{\mathcal{H}}) \rightarrow L$ extending f , such that the following statements hold:*

- (1) $\text{Op}^-(\mathcal{H})$ is consonent in $\text{Op}^-(\tilde{\mathcal{H}})$.
- (2) For each $i \in [n]$, there exists $W_i \in \text{Op}^-(\tilde{\mathcal{H}})$ such that $U_i \subseteq V_i \cup W_i$ and $g(W_i) \leq \gamma_i$.

Proof. Apply successively Lemma 10.7 to (U_1, V_1, γ_1) up to (U_n, V_n, γ_n) . \square

11. REPRESENTING COUNTABLE COMPLETELY NORMAL LATTICES

This section is devoted to a proof of our main theorem (Theorem 11.1), together with a short discussion of some of its corollaries.

Theorem 11.1. *Every countable completely normal distributive lattice with zero is isomorphic to $\text{Id}_c G$, for some Abelian ℓ -group G .*

Proof. Our goal is to represent a countable completely normal distributive lattice L with zero. The lattice \bar{L} , obtained from L by adding a new top element, is also completely normal, and L is an ideal of \bar{L} , so, by Lemma 3.1, any representation of \bar{L} as $\text{Id}_c \bar{G}$, for an Abelian ℓ -group \bar{G} , yields $L \cong \text{Id}_c G$ for an ℓ -ideal G of \bar{G} . Hence, it suffices to consider the case where L is bounded.

We fix a generating subset $\{a_n \mid n \in \omega\}$ of L .

Denote by $\mathcal{H}_{\mathbb{Z}} = \{H_n \mid n \in \omega\}$ the set of all integral hyperplanes of $\mathbb{R}^{(\omega)}$. Moreover, let $\{(U_n, V_n, \gamma_n) \mid n \in \omega\}$ be an enumeration of all triples (U, V, γ) , where $U, V \in \text{Op}^-(\mathcal{H}_{\mathbb{Z}})$ and $\gamma \in L$.

We construct an ascending chain $(\mathcal{H}_n \mid n \in \omega)$ of nonempty finite subsets of $\mathcal{H}_{\mathbb{Z}}$, with union $\mathcal{H}_{\mathbb{Z}}$, together with an ascending sequence $(f_n \mid n \in \omega)$ of 0,1-lattice homomorphisms $f_n: \text{Op}(\mathcal{H}_n) \rightarrow L$, as follows.

Take $\mathcal{H}_0 \stackrel{\text{def}}{=} \{\Delta_0\}$ (cf. Section 10); so $\text{Op}(\mathcal{H}_0) = \{\emptyset, \Delta_0^+, \Delta_0^-, \Delta_0^+ \cup \Delta_0^-, \mathbb{R}^{(\omega)}\}$ is isomorphic to J_2 (cf. Section 7). Let $f_0: \text{Op}(\mathcal{H}_0) \rightarrow \{0, a_0, 1\}$ be the unique homomorphism such that $f_0(\Delta_0^+) = a_0$, $f_0(\Delta_0^-) = 0$, and $f_0(\mathbb{R}^{(\omega)}) = 1$.

Suppose $f_n: \text{Op}(\mathcal{H}_n) \rightarrow L$ already constructed.

Let $n = 3m$ for some integer m , denote by k the first nonnegative integer outside $\text{supp}(\mathcal{H}_n)$, and set $\mathcal{H}_{n+1} \stackrel{\text{def}}{=} \mathcal{H}_n \cup \{\Delta_k\}$. By Lemma 10.3, there is a unique lattice homomorphism $f_{n+1}: \text{Op}(\mathcal{H}_{n+1}) \rightarrow L$, extending f , such that $f_{n+1}(\Delta_k^+) = a_m$ and $f_{n+1}(\Delta_k^-) = 0$. This will take care of the surjectivity of the restriction, to $\text{Op}^-(\mathcal{H}_{\mathbb{Z}})$, of the union of the f_n .

Let $n = 3m + 1$ for some integer m , and set $\mathcal{H}_{n+1} \stackrel{\text{def}}{=} \mathcal{H}_n \cup \{H_m\}$. Since L is completely normal and the range of f_n is finite, there is a finite sublattice S of L such that the range of f_n is consonant in S . By Lemma 9.4, f_n extends to a lattice homomorphism f_{n+1} from $\text{Op}(\mathcal{H}_{n+1})$ to S , thus to L . This will take care of the union of all f_n be defined on $\text{Op}(\mathcal{H}_{\mathbb{Z}})$.

Let, finally, $n = 3m + 2$ for some integer m . By Lemma 10.8, there is a finite subset \mathcal{H}_{n+1} of $\mathcal{H}_{\mathbb{Z}}$, containing \mathcal{H}_n , such that $\text{Op}(\mathcal{H}_n)$ is consonant in $\text{Op}(\mathcal{H}_{n+1})$, together with an extension $f_{n+1}: \text{Op}(\mathcal{H}_{n+1}) \rightarrow L$, such that for every $k \leq n$, if $\{U_k, V_k\} \subseteq \text{Op}^-(\mathcal{H}_n)$ and $f_n(U_k) \leq f_n(V_k) \vee \gamma_k$, then $f_{n+1}(U_k \setminus_{\text{Op}^-(\mathcal{H}_{n+1})} V_k) \leq \gamma_k$. This will take care of the union of the f_n be *closed* (as defined in the statement of Lemma 3.2) on $\text{Op}^-(\mathcal{H}_{\mathbb{Z}})$.

The union f of all the f_n is a surjective lattice homomorphism from $\text{Op}(\mathcal{H}_{\mathbb{Z}})$ onto L . Furthermore, the restriction f^- of f to $\text{Op}^-(\mathcal{H}_{\mathbb{Z}})$ is a closed, surjective lattice homomorphism from $\text{Op}^-(\mathcal{H}_{\mathbb{Z}})$ onto L . Now by the Baker-Beynon duality (cf. Proposition 3.7), $\text{Id}_c F_\ell(\omega)$ is isomorphic to $\text{Lat}(\omega)$, which is identical to $\text{Op}^-(\mathcal{H}_{\mathbb{Z}})$ (cf. Lemma 8.7). Hence, the map f^- induces a closed, surjective lattice homomorphism $g: \text{Id}_c F_\ell(\omega) \rightarrow L$. By Lemma 3.5, this map factors through an isomorphism from $\text{Id}_c(F_\ell(\omega)/I)$ onto L , for a suitable ℓ -ideal I of $F_\ell(\omega)$. \square

Recall that Delzell and Madden's results in [14] imply that Theorem 11.1 does not extend to the uncountable case.

Corollary 11.2. *A second countable generalized spectral space X is homeomorphic to the ℓ -spectrum of an Abelian ℓ -group iff it is completely normal.*

Proof. By Theorem 11.1 and Lemma 4.7, it remains to prove that if the topology of X has a countable basis, say \mathcal{B} , then $\mathcal{K}(X)$ is countable. Every $A \in \mathcal{K}(X)$ is the union of a subset \mathcal{B}_A of \mathcal{B} , which, by the compactness of A , may be taken finite. Since the assignment $A \mapsto \mathcal{B}_A$ is one-to-one, it determines a one-to-one map from $\mathcal{K}(X)$ into the finite subsets of \mathcal{B} ; whence $\mathcal{K}(X)$ is countable. \square

Recall that the complete normality of a spectral space X is equivalent to the specialization order on X be a root system (cf. Proposition 4.4).

It is well known that the lattice $\mathcal{C}(G)$, of all convex ℓ -subgroups of any ℓ -group (not necessarily Abelian) G , is the ideal lattice a completely normal distributive lattice with zero (see Iberkleid, Martínez, and McGovern [26, Section 1.2] for a short overview). Of course, in the Abelian case, $\mathcal{C}(G)$ is isomorphic to the ideal lattice of $\text{Id}_c G$. A direct application of Theorem 11.1 yields the following.

Corollary 11.3. *For every countable ℓ -group G , there exists a countable Abelian ℓ -group A such that $\mathcal{C}(G) \cong \mathcal{C}(A)$.*

The results of Kenoyer [28] and McCleary [31] imply that Corollary 11.3 does not extend to the uncountable case. The question handled in both papers was credited,

in the second paper, to Paul Conrad in a Workshop on ordered groups, Bowling Green, Ohio, 1985.

The real spectrum $\text{Spec}_r R$, of any commutative ring R , is a completely normal spectral space (cf. Coste and Roy [12], Dickmann [16]). Moreover, it has a basis of open sets which is indexed by finite sequences of elements of R ; in particular, if R is countable, then $\text{Spec}_r R$ is second countable. A direct application of Corollary 11.2 yields the following.

Corollary 11.4. *For every countable, unital, commutative ring R , there exists a countable Abelian ℓ -group A with unit such that $\text{Spec}_r R$ and $\text{Spec}_\ell A$ are homeomorphic.*

12. DISCUSSION

12.1. Ideal lattices of dimension groups. A partially ordered Abelian group G is a *dimension group* if G is directed, unperforated (i.e., $mx \geq 0$ implies that $x \geq 0$, whenever $x \in G$ and m is a positive integer), and G^+ satisfies the Riesz refinement property (cf. Goodearl [19]). The construction $\text{Id}_c G$, for an Abelian ℓ -group G , extends naturally to arbitrary dimension groups, by replacing “ ℓ -ideal” by “directed convex subgroup” (in short *ideal*). However, now $\text{Id}_c G$ is only a $(\vee, 0)$ -semilattice. This semilattice is always distributive (i.e., it satisfies the Riesz refinement property), but it may not be a lattice. In fact, *Every countable distributive $(\vee, 0)$ -semilattice is isomorphic to $\text{Id}_c G$ for some countable dimension group G* (this is implicit in Bratteli and Elliott [7], Hofmann and Thayer [25], Bergman [2], and explicitly stated as Goodearl and Wehrung [20, Theorem 5.2]); *moreover, the countable size is optimal* (Wehrung [41]).

In particular, it follows from Goodearl and Wehrung [20, Theorem 4.4] that for every distributive lattice L with zero, there exists a dimension group G such that $\text{Id}_c G \cong L$ (without any restriction on the cardinality of L). One could then hope to be able to apply Theorem 1 of Elliott and Mundici [18], in order to infer that if L is completely normal, then G is lattice-ordered. However, this would already fail for the lattice $L = \mathbf{D}_{\omega_1}$ of Example 5.5, simply because \mathbf{D}_{ω_1} is not ℓ -representable. The problem lies in the fact that one cannot read, on $\text{Id}_c G$ (equivalently, on the spectrum of G) alone, that every prime quotient of G be totally ordered. This fact is illustrated by the following much easier example, also implied on page 181 in [18]: let G be any non totally ordered simple dimension group (e.g., $G = \mathbb{Q} \times \mathbb{Q}$ with positive cone consisting of all (x, y) with either $x = y = 0$ or $x > 0$ and $y > 0$). Then $\text{Id}_c G \cong \mathbf{2}$, yet G is not totally ordered.

12.2. Lattices of ℓ -ideals in non-Abelian ℓ -groups. It is proved in Růžička, Tůma, and Wehrung [36, Theorem 6.3] that *Every countable distributive $(\vee, 0)$ -semilattice is isomorphic to $\text{Id}_c G$ for some ℓ -group G ; moreover, this result does not extend to semilattices of cardinality \aleph_2* . The gap at size \aleph_1 is not filled yet.

12.3. Open problems. While Example 5.5 gives an example of a non- ℓ -representable distributive lattice with an ℓ -representable elementary sublattice, we do not know whether the opposite situation may occur:

Problem 1. Let D be an elementary sublattice of a distributive lattice E . If E is ℓ -representable, is D also ℓ -representable?

While Theorem 11.1 implies a positive answer to Problem 1 in the countable case, the uncountable case remains open. Analogues of Problem 1, for other functors than Id_c on Abelian ℓ -groups, may lead to different situations. Consider, for example, the functor \mathbf{L} , which to every von Neumann regular ring R associates the lattice $\mathbf{L}(R)$ of all principal right ideals of R . Lattices of the form $\mathbf{L}(R)$ are said to be *coordinatizable*. In [42], we construct a countable, coordinatizable lattice with a non-coordinatizable elementary sublattice. In that paper, it is also proved that the class of all coordinatizable lattices is not the class of models of any $\mathcal{L}_{\infty, \infty}$ sentence. This suggests the following problem.

Problem 2. Prove that the class of all ℓ -representable distributive lattices is not the class of models of any $\mathcal{L}_{\infty, \infty}$ sentence.

Finally, the analogy between ℓ -spectra and real spectra (cf. Section 1.2), together with Corollary 11.2, suggests the following problem.

Problem 3. Is every second countable completely normal spectral space homeomorphic to the real spectrum of some commutative, unital ring?

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