FORBIDDEN FORESTS IN PRIESTLEY SPACES

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Dedicated to the memory of Japie Vermeulen

ABSTRACT. We present a first order formula characterizing the distributive lattices L whose Priestley spaces $\mathcal{P}(L)$ contain no copy of a forest T. For Heyting algebras L, prohibiting a poset T in $\mathcal{P}(L)$ is characterized by equations iff T is a tree. We also give a condition characterizing the distributive lattices whose Priestley spaces contain no copy of a forest with a single additional point at the bottom.

1. Introduction

Priestley duality provides an important link between distributive lattices and (special) ordered topological spaces. Some properties of distributive lattices L are well-known to be expressed in forbidden configurations in the order structure of the corresponding spaces $\mathcal{P}(L)$. Thus, for instance, L is a Boolean algebra iff $\mathcal{P}(L)$ has just one layer, that is, if it contains no non-trivial chain. Or L is relatively normal iff $\mathcal{P}(L)$ is a forest, that is, if it contains no copy of the three element set $\{t_0, t_1, t_2\}$, where $t_0 < t_1, t_2$ and t_1 and t_2 are unrelated. Or there are the distributive lattices of Adams and Beazer characterized by non-existence of an n-chain in $\mathcal{P}(L)$.

The question naturally arises as to whether, given a finite poset T, the lattices L for which $\mathcal{P}(L)$ does not contain a copy of T can be characterized by a first order condition in the language of lattice theory. In this article we answer this question in the positive for trees and forests T, and for their duals. Moreover, for Heyting algebras L we show that trees are precisely the forbidden configurations which determine subvarieties (or, equivalently, subquasivarieties) of the variety of Heyting algebras.

The authors continue to investigate the general problem: to find "nice" conditions characterizing those lattices whose Priestley spaces admit no copy of a given poset. In this article, the techniques developed for forests are modified to treat forests with a single additional point at the bottom; this is Theorem 5.6. The condition that arises, however, is not first order on its face, and we do not know if a first order condition exists. Many more types of posets can be handled similarly, and in fact a solution

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Date: June 27, 2001.

1991 *Mathematics Subject Classification.* Primary: 06D50, 06D20; Secondary: 06D22.

Key words and phrases. distributive lattice, trees and forests, Priestley duality.

The first author would like to express his gratitude to the Center for Theoretical Studies for affording him the opportunity to spend a delightful and productive sabbatical year in Prague.

The second author would like to express his thanks to the Institute of Theoretical Computer Science (ITI) at Charles Universiy and to the Anne and Ullis Gudder Trust for making visits to Denver possible.

to the general problem seems possible. But these results constitute another article in preparation.

2. Preliminaries

A *Priestley space* is an ordered compact space $(X, \tau, \leq)$ such that for any two $x, y \in X$ with $x \not\leq y$ there is a closed open increasing $U \subseteq X$ such that $x \in U$ and $y \notin U$. The category of Priestley spaces and monotone continuous maps will be denoted by

$$\mathbf{PSp}.$$

There is the famous *Priestley duality* (see, e.g., [10], [11]) between **PSp** and the category

$$\mathbf{DLat}$$

of bounded distributive lattices. The equivalence functors

$$\mathcal{P} : \mathbf{DLat} \to \mathbf{PSp}^{\mathrm{op}}, \quad \mathcal{D} : \mathbf{PSp} \to \mathbf{DLat}^{\mathrm{op}}$$

can be give as

$$\begin{aligned} &\mathcal{P}(L) = \{x \mid x \text{ is a proper prime ideal on } L\}, && \mathcal{P}(h)(x) = h^{-1}[x], \\ &\mathcal{D}(X) = \{U \mid U \text{ is a clopen decreasing subset of } X\}, && \mathcal{D}(f)(U) = f^{-1}[U], \end{aligned}$$

$\mathcal{P}(L)$ is endowed with a suitable topology and partially ordered by inclusion; in this article we will be concerned solely with the partial order.

Finite Priestley spaces are the finite partially ordered sets (with the discrete topologies). Note that, however, the functor $\mathcal{D}$ associates with a finite $(X, \leq)$ the (lower) Alexandroff topology (not the discrete one) and that thus the restriction of $\mathcal{D}$ to the finite case coincides with the restriction of the open-set-lattice functor $\Omega : \mathbf{Top} \to \mathbf{Frm}$ to finite T_0-spaces. (**Frm** is the category of frames, that is, complete lattices with the distributivity $(\bigvee a_i) \wedge b = \bigvee(a_i \wedge b)$.)

The full subcategory of **DLat** consisting of the Heyting lattices, i.e., those lattices of **DLat** admitting the Heyting operation, will be denoted by

$$\mathbf{HLat}.$$

We will also consider the variety of Heyting algebras *with Heyting homomorphisms* and denote it by

$$\mathbf{Hey}.$$

The letters a, b, c and d, often decorated by subscripts or primes, will be reserved for the elements of the distributive lattices. The prime ideals on such lattices L (elements of $\mathcal{P}(L)$) will be typically denoted by x, y, z. For a subset $A \subseteq L$ we use

$$\begin{aligned} \mathsf{Idl}(A) =& \{a \mid a \leq \bigvee A_0 \text{ for some finite } A_0 \subseteq A\} \text{ and} \\ \mathsf{Fltr}(A) =& \{a \mid a \geq \bigwedge A_0 \text{ for some finite } A_0 \subseteq A\} \end{aligned}$$

to designate the ideal and filter, respectively, generated by A_0. The set of all *proper* ideals on L (ordered by inclusion) will be denoted by

$$\mathfrak{J}(L).$$

Definition 2.1. If A is an ideal and B a filter on L we set

$$\begin{aligned} A \downarrow B &\equiv \{c : \exists a \in A, b \in B \ (b \wedge c \leq a)\}, \\ A \uparrow B &\equiv \{c : \exists a \in A, b \in B \ (b \wedge c \leq a)\}. \end{aligned}$$

Obviously, $A \downarrow B$ is an ideal and $A \uparrow B$ is a filter. For general subsets $A, B \subseteq L$ we write $A \downarrow B$ meaning $\mathsf{Idl}(A) \downarrow \mathsf{Fltr}(B)$. For elements $a, b \in L$ we write $a \downarrow B$ and $A \downarrow b$ for $\{a\} \downarrow B$ and $A \downarrow \{b\}$. Thus for instance $a \downarrow b = \{c \mid b \wedge c \leq a\}$. The dual conventions apply to $A \uparrow B$ and $a \uparrow b$.

Lemma 2.2. *Let $A, B \subseteq L$. Then the following, and their duals, hold.*

1. *$A \subseteq A \downarrow B$.*
2. *$(A \downarrow B) \downarrow B = A \downarrow B$.*
3. *$A \downarrow B$ is proper iff $A \cap B = \emptyset$.*
4. *For an ideal A and a filter B such that $A \downarrow B$ is proper (that is, $A \cap B = \emptyset$) there is an $x \in \mathcal{P}(L)$ such that $A \subseteq x$ and $x \cap B = \emptyset$.*

Proof. We leave the proofs of the dual statements to the reader. (1) $1 \wedge a \leq a$. (2) If $c \in (A \downarrow B) \downarrow B$ there is a $d \in A \downarrow B$ and a $b \in B$ such that $b \wedge c \leq d$. There is an $a \in A$ and a $b' \in B$ such that $b' \wedge d \leq a$; hence $(b \wedge b') \wedge c \leq a$. (3) $A \downarrow B$ is proper iff $1 \notin A \downarrow B$ iff $b \nleq a$ for any $a \in A$ and $b \in B$.

(4) Using Zorn's lemma we obtain an ideal J maximal with respect to $J \supseteq A$ and $J \cap B = \emptyset$. J is prime, for if $c_1, c_2 \notin J$ it can only be because there exist $b_i \in \mathsf{Idl}\,(c_i, J) \cap B$, from which we get

$$b_1 \wedge b_2 \in \mathsf{Idl}\,(c_1, J) \cap \mathsf{Idl}\,(c_2, J) \cap B = \mathsf{Idl}\,(c_1 \wedge c_2, J) \cap B,$$

and this implies that $c_1 \wedge c_2 \notin J$. Put $x \equiv J$. □

The symbol T will designate a finite poset.

Definition 2.3. A map $m : T \to \mathfrak{J}(L)$ (resp. $m : T \to \mathcal{P}(L)$) is said to *monotone* if

$$\tau \leq t \Longrightarrow m(\tau) \subseteq m(t),$$

and m is said to be a *copy of T* if it is monotone and

$$\tau \nleq t \quad \Longrightarrow m(\tau) \nsubseteq m(t).$$

A mapping $a : T \to L$ is a *separator* of a monotone map $m : T \to \mathfrak{J}(L)$ (resp. $m : T \to \mathcal{P}(L)$) provided that for all $t, \tau \in T$,

$$a(\tau) \in m(t) \Longleftrightarrow t \nleq \tau.$$

We say that a *separates* m.

We introduce a handy notation.

Definition 2.4. For a map $a : T \to L$ define an associated map $a' : T \to L$ by the rule

$$a'(t) \equiv \bigvee_{t \nleq \tau} a(\tau), \quad t \in T.$$

Then a separates the monotone map m iff $a'(t) \in m(t)$ and $a(t) \notin m(t)$ for all $t \in T$.

Obviously a monotone map with a separator is a copy, whether in $\mathcal{I}(L)$ or $\mathcal{P}(L)$. The converse holds for monotone maps into $\mathcal{P}(L)$.

Lemma 2.5. *Each copy $x : T \to \mathcal{P}(L)$ has a separator.*

Proof. Fix $t \in T$. For each $\tau \nleq t$ choose a $b(\tau) \in x(\tau) \smallsetminus x(t)$ and set $a(t) = \bigwedge_{\tau \nleq t} b(\tau)$. Since $x(t)$ is prime, $a(t) \notin x(t)$, and of course $a(t) \in x(\tau)$ for all the $\tau \nleq t$. □

3. Prohibiting forests

In a poset we will write

$$\tau \prec t$$

and say that τ *is a descendent of* t, or that t *is an ascendent of* τ, if $\tau < t$ and if for every s, $\tau \leq s \leq t$ implies that either $s = \tau$ or $s = t$. Denote by

- $\max(T)$ the set of all maximal elements of T, and by
- $\min(T)$ the set of all minimal elements of T.

A finite poset T is said to be a *forest* if each $t \in T$ has at most one ascendent. A forest T with exactly one maximal element is called a tree, and its maximal element will be denoted by e_T, or simply by e. Obviously, forests are precisely the disjoint unions of trees. *From this point until Theorem 4.1 we assume T to be a forest.* Without this assumption the next result, which is crucial for our purposes, does not hold.

Proposition 3.1. *Let $a : T \to L$ separate the copy $J : T \to \mathfrak{J}(L)$. If*

$$J(t) \downarrow a(t) = J(t), \quad t \in T,$$

then there is a copy $x : T \to \mathcal{P}(L)$, separated by the same a, such that $x(t) \supseteq J(t)$ for all t.

Proof. First, for maximal elements t of T choose $x(t) \in \mathcal{P}(L)$ such that $x(t) \supseteq J(t)$ and $x(t) \cap \mathsf{Fltr}(a(t)) = \emptyset$, by Lemma 2.2(4). Then $a(t) \notin x(t)$, and for any other maximal t' we have $a(t') \in J(t) \subseteq x(t)$.

Now suppose J has already been extended as desired on an increasing subset T' of T containing $\max(T)$. Let T'' be T' augmented by all the descendents τ of elements t minimal in T'. For $\tau \in T'' \smallsetminus T'$ with ascendent t we have

$$J(\tau) \cap \mathsf{Fltr}((L \smallsetminus x(t)) \cup \{a(\tau)\}) = \emptyset.$$

Indeed, otherwise we would have $b \wedge a(\tau) \in J(\tau)$ for some $b \notin x(t)$ and hence $b \in J(\tau) \downarrow a(\tau) = J(\tau) \subseteq J(t) \subseteq x(t)$, a contradiction. Choose by Lemma 2.2(4) an $x(\tau)$ in $\mathcal{P}(L)$ such that $x(\tau) \supseteq J(\tau)$ and $x(\tau) \cap \mathsf{Fltr}((L \smallsetminus x(t)) \cup \{a(\tau)\} = \emptyset$. In particular, $a(\tau) \notin x(\tau)$ and $a'(\tau) \in J(\tau) \subseteq x(\tau)$ by construction. When this process is complete, it is clear that we have a monotone map $x : T \to \mathcal{P}(L)$ separated by a. □

Definition 3.2. Let T be a forest and $a : T \to L$ any mapping. Define $I_a : T \to \mathfrak{J}(L)$ inductively by setting

$$I_a(t) \equiv \left(\bigcup_{\tau < t} I_a(\tau), a'(t) \right) \downarrow a(t).$$

A couple of remarks about Definition 3.2 are in order. We subscribe to the convention that a union over an empty index set is empty, so that for $t \in \min(T)$ the definition reduces to $I_a(t) \equiv a'(t) \downarrow a(t)$. And in the presence of this equation, it is enough to require in addition only that

$$I_a(t) = \left(\bigcup_{\tau \prec t} I_a(\tau), a'(t) \right) \downarrow a(t)$$

for $t \in T \setminus \min(T)$.

Lemma 3.3. *If a separates a copy $x : T \to \mathcal{P}(L)$ then $I_a(t) \subseteq x(t)$ for all $t \in T$.*

Proof. We induct on T from the bottom up. It $t \in \min(T)$ then any $c \in I_a(t)$ satisfies $c \wedge a(t) \leq a'(t) \in x(t)$. Since $a(t) \notin x(t)$ and $x(t)$ is prime, $c \in x(t)$. Assume that $I_a(\tau) \subseteq x(\tau)$ for all $\tau < t$. If $c \in I_a(t)$ we have

$$c \wedge a(t) \leq \bigvee_{\tau < t} b_\tau \vee a'(t)$$

for some $b_\tau \in I_a(\tau) \subseteq x(\tau) \subseteq x(t)$, $\tau < t$. But then since $a'(t) \in x(t)$ we see that $c \wedge a(t) \in x(t)$, and because $x(t)$ is prime and $a(t) \notin x(t)$, c must therefore lie in $x(t)$. □

Lemma 3.4. *Let $a : T \to L$ be any map. Then the following hold for all $t, \tau \in T$.*

1. *If $\tau \leq t$ then $I_a(\tau) \cup \{a(\tau)\} \subseteq I_a(t)$.*
2. *$I_a(t) \downarrow a(t) = I_a(t)$.*

Proof. (1) follows from Lemma 2.2(1) and (2) follows from Lemma 2.2(2). □

Theorem 3.5. *$\mathcal{P}(L)$ does not contain a copy of a forest T iff for each $a : T \to L$ there is a $t \in \max(T)$ such that $I_a(t)$ is improper.*

Proof. Let $\mathcal{P}(L)$ contain a copy $x : T \to L$ separated by $a : T \to L$. Then by Lemma 3.3 each $I_a(t)$ lies in the proper ideal $x(t)$. On the other hand, if there is an $a : T \to L$ such that $I_a(t)$ is proper for all t then from Lemmas 2.2(3) and 3.4(2) we can conclude that for all $t \in T$, $a(t) \notin I_a(t)$ since otherwise $I_a(t)$ would be improper. Furthermore, Lemma 3.4(1) shows that $a'(t) \in I_a(t)$ for all t. Since I_a is monotone there is a copy $x : T \to \mathcal{P}(L)$ separated by a by Proposition 3.1. □

Our next objective is to show that the absence of a copy of T in $\mathcal{P}(L)$ can be characterized by the satisfaction in L of a specific first order sentence ψ_T in the language of lattice theory (Corollary **??**). This requires that we take a closer look at exactly how the ideals $I_a(t)$, $t \in T$, are built up. The key insight is contained in Lemma 3.9.

Definition 3.6. Let $a : T \to L$ be any function. A *T-supplement of a* is a function $c : T \to L$ such that for all $t \in T$,

$$a(t) \wedge c(t) \leq \bigvee_{\tau<t} c(\tau) \vee a'(t).$$

A *T-complement of a* is a T-supplement c for which $c(t) = 1$ for some $t \in \max(T)$.

A couple of remarks about Definition 3.6 are in order. We subscribe to the convention that a join over an empty index set is 0, so that for $t \in \min(T)$ the definition reduces to $a(t) \wedge c(t) \leq a'(t)$. And in the presence of this condition it is enough to require in addition only that

$$a(t) \wedge c(t) \leq \bigvee_{\tau \prec t} c(\tau) \vee a'(t).$$

for $t \in T \smallsetminus \min(T)$.

Example 3.7. *Denote by* $\mathbf{n}$ *the chain*

$$\{0 < 1 < \cdots < n\}.$$

An $\mathbf{n}$*-complement of a system* $(a_0, a_1, \ldots, a_n)$ *is a* $(c_0, c_1, \ldots, c_n)$ *such that*

$$\begin{aligned} a_0 \wedge c_0 &= 0, \\ a_k \wedge c_k &\leq a_{k-1} \vee c_{k-1} \quad \text{for} \quad 0 < k \leq n, \text{ and} \\ c_n &= 1. \end{aligned}$$

Thus, $(a, 1)$ *has exactly one* $\mathbf{1}$*-complement, namely the* $(c, 1)$ *with* c *the complement of* a *in* L.

Observe that if $(c_0, \ldots, c_{n-1}, c_n)$ *is an* $\mathbf{n}$*-complement of a system of the form* $(a_0, \ldots, a_{n-1}, 1)$ *then it is also an* $\mathbf{n}$*-complement of* $(a_0, \ldots a_{n-1}, a_n)$ *for any* a_n*. Thus every system* $(a_0, \ldots, a_n)$ *has an* n*-complement iff for every smaller system* $(a_0, \ldots a_{n-1})$ *there is some* $(c_0, \ldots, c_{n-1})$ *such that*

$$\begin{aligned} a_0 \wedge c_0 &= 0, \\ a_k \wedge c_k &\leq a_{k-1} \vee c_{k-1} \quad \text{for} \quad 0 < k < n, \text{ and} \\ a_{n-1} \vee c_{n-1} &= 1. \end{aligned}$$

Example 3.8. *Let* T *be an antichain. Then* $a : T \to L$ *has a* T*-complement iff there is a* $t \in T$ *such that*

$$a(t) \leq \bigvee_{t \neq \tau} a(\tau).$$

Theorem 3.5 can now be reformulated as Theorem 3.10, whose proof follows directly from the following lemma.

Lemma 3.9. *Let $a : T \to L$ be any monotone map. Then for all $t \in T$,*

$$I_a(t) = \{c(t) : c \text{ is a } T\text{-supplement of } a\}.$$

Proof. Let us abbreviate the set on the right of the displayed equality by I_t. A simple induction on T, based on Definitions 3.2 and 3.6, is enough to show that $I_t \subseteq I_a(t)$ for all $t \in T$. A simple induction also suffices to establish the opposite containment. For if $b \in I_a(t)$ then there are elements $b_\tau \in I_a(\tau)$, $\tau < t$, for which

$$b \wedge a(t) \leq \bigvee_{\tau < t} b_\tau \vee a'(t).$$

By the inductive hypothesis each b_τ is of the form $c_\tau(\tau)$ for some T-supplement c_τ of a. If we combine these into a single T-supplement c, defined by the rule

$$c(s) \equiv \begin{cases} \bigvee_{\tau<t} c_\tau(s) & \text{if} \quad s < t, \\ b & \text{if} \quad s = t, \\ 0 & \text{if} \quad s \nleq t \end{cases},$$

we get a T-supplement to a with the feature that $c(t) = b$. This completes the proof. □

Theorem 3.10. *$\mathcal{P}(L)$ does not contain a copy of T iff each mapping $a : T \to L$ has a T-complement. If T is a tree this in turn is equivalent to requiring that each $a : T \to L$ such that $a(e_T) = 1$ has a T-complement.*

Corollary 3.11. *12For any forest T there is a sentence ψ_T in the first order language of lattice theory such that for any bounded distributive lattice L, $\mathcal{P}(L)$ contains no copy of T iff ψ_T holds in L. Moreover, ψ_T is of the form $\forall\exists\phi$, where ϕ is quantifier-free and built up from atomic formulas by conjunction and disjunction. If T is a tree then ϕ is a conjunction of atomic formulas.*

Proof. Let x_t, y_t, $t \in T$, be syntactic variables. We think of maps $a, c : T \to L$ as assigning values $a(t)$ to variables x_t and $c(t)$ to variables y_t, $t \in T$. Furthermore, a look at Definition 3.6 reveals that most of the inequalities which make c a T-complement of a are combined by conjunction, with the only disjunction being

$$y_{t_1} = 1 \text{ or } y_{t_2} = 1 \text{ or } \ \ldots \ \text{ or } y_{t_n} = 1,$$

where $\max(T) = \{t_1, t_2, \ldots, t_n\}$. If T is a tree there is only a single disjunct, i.e., the formula is atomic. The result follows from Theorem 3.10. □

Example 3.12 (Example 3.7 revisited)**.** *We obtain the characterization of Adams and Beazer [1] stating that $\mathcal{P}(L)$ contains no chain of length n iff for any $a_0, a_1, \ldots, a_{n-1}$ in L there are $c_0, c_1, \ldots, c_{n-1}$ in L such that*

$$\begin{aligned} a_0 \wedge c_0 &= 0, \\ a_k \wedge c_k &\leq a_{k-1} \vee c_{k-1} \quad \textit{for} \quad 0 < k < n, \quad \textit{and} \\ a_{n-1} \vee c_{n-1} &= 1. \end{aligned}$$

In particular, the order in $\mathcal{P}(L)$ is trivial iff L is a Boolean algebra.

Example 3.13 (Example 3.8 revisited)**.** *Each antichain in $\mathcal{P}(L)$ has at most $n-1$ elements iff for any $a_1, \ldots, a_n$ in L there is a k such that*

$$a_k \leq \bigvee_{j \neq k} a_j.$$

Example 3.14. *No antichain with at least n elements, n fixed and ≥ 2, has an upper bound in $\mathcal{P}(L)$ iff for any $a_1, \ldots, a_n \in L$ there are $c'_1, \ldots, c'_n \in L$ such that for all k, $a_k \wedge c'_k \leq \bigvee_{j \neq k} a_j$, and $\bigvee_j a_j \vee \bigvee_j c'_j = 1$. Replacing the c'_k by $c_k = c'_k \vee \bigvee_{j \neq k} a_j$, we see that no antichain with at least n elements, n fixed and ≥ 2, has an upper bound in $\mathcal{P}(L)$ iff for any $a_1, \ldots, a_n \in L$ there are $c_1, \ldots, c_n \in L$ such that for all k,*

$$a_k \wedge c_k \leq \bigvee_{j \neq k} a_j, \quad \textit{and} \quad \bigvee_j c_j = 1.$$

Example 3.15. *$\mathcal{P}(L)$ has no independent system of n $\mathbf{1}$-chains iff for any $a_1, \ldots, a_n$ and $b_1 \ldots, b_n$ in L there are $c_1, \ldots, c_n$ in L and a k_0 such that*

$$\forall k, \ a_k \wedge c_k \leq \bigvee_{j \neq k} a_j \vee \bigvee_{j \neq k} b_j, \quad \textit{and } k_0, \quad b_{k_0} \leq a_{k_0} \vee c_{k_0}.$$

The characterizations in the theorems above can be easily modified for dual trees and dual forests. Denote by $|\mathcal{P}(L)|$ the poset structure of $\mathcal{P}(L)$. A prime ideal in L is a prime filter in L^{op}, and vice versa. Thus we have an anti-isomorphism

$$(J \mapsto L \smallsetminus J) : |\mathcal{P}(L)| \to |\mathcal{P}(L^{\mathrm{op}})|$$

and

$$|\mathcal{P}(L)|^{\mathrm{op}} \cong |\mathcal{P}(L^{\mathrm{op}})|.$$

Hence, T^{op} is forbidden in $\mathcal{P}(L)$ iff T is forbidden in $\mathcal{P}(L^{\mathrm{op}})$. For example, since T is isomorphic to T^{op} in Examples 3.12 and 3.13, the conditions that arise there must be equivalent to their duals. In fact, they are self-dual. This is obvious in the case of Exercise 3.12; to see that the condition of Example 3.13 is self dual, suppose that for any subset $\{a_i : 1 \leq i \leq n\} \subseteq L$ there is a k such that $a_k \leq \bigvee_{j \neq k} a_j$. Apply this condition to $\left\{\bigwedge_{i \neq j} a_i : 1 \leq i \leq n\right\}$ to get a k for which

$$\bigwedge_{i \neq k} a_i \leq \bigvee_{j \neq k} \bigwedge_{i \neq j} a_i = \bigvee_{j \neq k} \left(a_k \wedge \bigwedge_{i \neq j,k} a_i \right) = a_k \wedge \bigvee_{j \neq k} \bigwedge_{i \neq j,k} a_i,$$

which shows that $a_k \geq \bigwedge_{i \neq k} a_i$, i.e., L satisfies the dual condition.

We close this section with a brief discussion of normal and relatively normal lattices. Recall that a distributive lattice L is *normal* if for any two $a_1, a_2 \in L$ such that $a_1 \vee a_2 = 1$ there are $c_1, c_2 \in L$ such that $a_1 \vee c_1 \geq a_2$, $a_1 \vee c_2 \geq a_1$, and $c_1 \wedge c_2 = 0$. This is an extrapolation of the homonymous notion from topology: a space is normal iff the lattice of open sets is normal in the sense just defined. The following characterization of normal lattices in terms of their Priestley spaces is well known and is essentially due to Monteiro ([8], [9]), who proved it in the context of the open set lattice of a space. We offer a proof here only because the ideas are very close in spirit to those of the rest of this article.

Proposition 3.16. *The following are equivalent.*

1. *L is normal.*
2. *Every point of $\mathcal{P}(L)$ lies below a unique maximal point.*
3. *In $\mathcal{P}(L)$, any pair of elements with a common lower bound must have a common upper bound.*

Proof. The equivalence of (2) and (3) is clear upon reflecting on a general fact about Priestley spaces: every point lies below a maximal point and above a minimal point. That is because the family of prime ideals of a distributive lattice is closed under both the union and intersection of chains.

Suppose that L is normal, and assume for the sake of argument that $\mathcal{P}(L)$ contains a point x_3 which lies below two distinct maximal points x_1 and x_2. Since $\mathsf{Idl}(x_1, x_2)$ is improper, there are $a_1 \in x_1 \setminus x_2$ and $a_2 \in x_2 \setminus x_1$ such that $a_1 \vee a_2 = \top$. Find $c_1, c_2 \in L$ for which $a_1 \vee c_2 = c_1 \vee a_2 = 1$ and $c_1 \wedge c_2 = 0$. Then because x_3 is prime, it contains either c_1 or c_2. But if $c_1 \in x_3$ then $1 = c_1 \vee a_2 \in x_2$ and if $c_2 \in x_3$ then $1 = a_1 \vee c_2 \in x_1$, a contradiction in either case. We conclude that every point of $\mathcal{P}(L)$ lies below a unique maximal point.

Now suppose that L is not normal; this means we have elements a_1 and a_2 for which $a_1 \vee a_2 = 1$ but $\mathsf{Fltr}(a_1 \uparrow a_2, a_2 \uparrow a_1)$ is proper. Let $\mathcal{F}$ designate the set of pairs (F_1, F_2) of filters on L with the following properties.

- $a_1 \uparrow a_2 \subseteq F_1$ and $a_2 \uparrow a_1 \subseteq F_2$.
- $\mathsf{Fltr}(a_1 \uparrow F_1, a_2 \uparrow F_2)$ is proper.

Note that $\mathcal{F}$ is nonempty because it contains $(a_1 \uparrow a_2, a_2 \uparrow a_1)$ by hypothesis. Also note that, when ordered by the rule

$$(F_1, F_2) \leq (K_1, K_2) \iff F_1 \subseteq K_1 \text{ and } F_2 \subseteq K_2,$$

$\mathcal{F}$ is closed under joins of chains and so contains a maximal element (K_1, K_2). Observe that $K_1 = a_1 \uparrow K_1$ and $K_2 = a_2 \uparrow K_2$ by maximality, so that $a_1 \notin K_1$ and $a_2 \notin K_2$ lest the filters be improper. We claim that K_1 and K_2 are prime. To verify this claim consider $b, b' \notin K_1$. This implies that there are elements $k_1, k_1' \in K_1$ and $k_2, k_2' \in K_2$ such that

$$b \wedge k_1 \wedge k_2 = b' \wedge k_1' \wedge k_2' = 0.$$

But if we set $k_1'' \equiv k_1 \wedge k_1' \in K_1$ and $k_2'' \equiv k_2 \vee k_2' \in K_2$ we get

$$(b \vee b') \wedge k_1'' \wedge k_2'' = 0,$$

which implies $b \vee b' \notin K_1$. The proof that K_2 is prime is similar.

Let x_1, x_2 be maximal elements of $\mathcal{P}(L)$ containing the prime ideals $L \setminus K_1$ and $L \setminus K_2$, respectively. Then $a_1 \in x_1 \setminus x_2$ and $a_2 \in x_2 \setminus x_1$, so the maximal elements are distinct. Let x_2 be maximal among ideals disjoint form $\mathsf{Fltr}(K_1, K_2)$. Then x_3 is a common lower bound for x_1 and x_2 in $\mathcal{P}(L)$. ∎

A lattice L is *relatively normal* if for any two $a_1, a_2 \in L$ there are c_1, c_2 such that $a_1 \vee c_1 \geq a_2$, $a_1 \vee c_2 \geq a_1$, and $c_1 \wedge c_2 = 0$. In topology this corresponds to the requirement that each open subspace of the space in question is normal. Relative normality plays a fundamental, though sometimes unacknowledged, role in several areas of mathematics. For example, the lattice of cozero sets of a topological space is always relatively normal [7], and it is no accident that relative normality is the key ingredient in the construction of what are called Wallman covers of topological spaces [5]. A second example is the penetrating and beautiful structure theory of lattice-ordered groups (ℓ-groups for short), developed by Conrad and his students ([3] is the best general reference), based on the lattice of convex ℓ-subgroups. This lattice is algebraic, i.e., complete and generated by its compact elements, and the compact elements themselves form a relatively normal sublattice. The class of just such lattices, devoid of any group structure, was subsequently extensively investigated by Tsinakis and his students ([4], [12], [13]). Their work shows that a large part of the ℓ-group structure theory comes directly from the lattice theory, and in fact from the relative normality of the sublattice of compact elements of the lattice of convex ℓ-subgroups.

We content ourselves here with the observation that the relative normality of L is equivalent to $\mathcal{P}(L)$ being a forest. This is essentially due to Monteiro ([8], [9]), who proved it in the context of the open set lattice of a space.

Proposition 3.17. *L is relatively normal iff $\mathcal{P}(L)$ is a forest.*

Proof. The definition of relative normality is the dual of the condition of Example 3.14 for $n = 2$. Thus L is relatively normal iff no two unrelated elements of $\mathcal{P}(L)$ have a common lower bound, i.e., iff $\mathcal{P}(L)$ is a forest. □

4. Equations forbidding trees

We show that if L is a Heyting algebra then each map $a : T \to L$ has a largest T-supplement, which we will designate a^T. (We order maps $a, b : T \to L$ by declaring that $a \geq b$ if $a(t) \geq b(t)$ for all $t \in T$.) Thus any such map a will have a T-complement iff a^T is a T-complement. This fact eliminates the existential quantifier in the sentence ψ_T of Corollary **??**. Consequently the Heyting algebra whose Priestley spaces contain no copy of a given fixed tree form a variety. The surprise is that only trees have this property; this is the content of Theorem 4.9.

For the rest of this section we assume that L is a Heyting lattice, i.e., that L is a bounded distributive lattice which admits the Heyting implication operation $\to$. When actually equipped with this operation, L becomes a Heyting algebra and the maps are required to preserve $\to$ as well as the lattice structure. We ask the reader to keep in mind the defining feature of $\to$, namely that for $a, b, c \in L$,

$$a \leq b \to c \iff a \wedge c \leq b. \tag{$*$}$$

Definition 4.1. Let L be a Heyting algebra. For $a : T \to L$ define $a^T : T \to L$ inductively as follows.

- for $t \in \min(T)$,

$$a^T(t) \equiv a(t) \to \bigvee_{t \not\leq \tau} a(\tau),$$

- for $t \in T \setminus \min(T)$,

$$a^T(t) \equiv a(t) \to \left(\bigvee_{\tau \prec t} a^T(\tau) \vee \bigvee_{\tau \prec t} a(\tau) \right).$$

Lemma 4.2. *Let L be a Heyting algebra. For any map $a : T \to L$, a^T is the largest T-supplement of a.*

Proof. Compare Definitions 3.6 and 4.1 in light of (∗). □

Corollary 4.3. *Let L be a Heyting algebra. Then a map $a : T \to L$ has a T-complement iff a^T is a T-complement.*

Corollary 4.4. *Let L be a Heyting algebra. For any map $a : T \to L$,*

$$I_a(t) = \mathsf{Idl}\left(a^T(t)\right)$$

for all $t \in T$.

Corollary 4.5. *Let L be a Heyting algebra. $\mathcal{P}(L)$ contains no copy of T iff for every map $a : T \to L$ we have $a^T(t) = 1$ for some $t \in \max(T)$.*

Corollary 4.6. *Let L be a Heyting algebra and T be a tree with top element e. Then $\mathcal{P}(L)$ contains no copy of T iff $a^T(e) = 1$ for every map $a : T \to L$.*

Corollary 4.7. *For every tree T there is a finite set Θ of equations in the first order language of Heyting algebra, just one of which mentions $\to$, with the following property. For any Heyting algebra L, the Priestley space of (the underlying lattice of) L contains no copy of T iff the equations of Θ all hold in L.*

We need a technical lemma and a little notation. Let $f : S \to R$ be a monotone map between finite posets S and R. Regarded as a map between Priestley spaces, f dualizes to the lattice map $f^{-1} : \mathcal{D}(R) \to \mathcal{D}(S)$, where $\mathcal{D}(R)$ and $\mathcal{D}(S)$ designate the lattices of decreasing subsets of R and S, respectively, and where $f^{-1}(U)$ is simply $\{s : f(s) \in U\}$ for $U \in \mathcal{D}(R)$. Now $\mathcal{D}(R)$ and $\mathcal{D}(S)$ are certainly Heyting lattices; in fact, for $U, V \in \mathcal{D}(R)$

$$U \to V = \{r : D(r) \cap U \subseteq V\},$$

where $D(r)$ designates the decreasing subset of R generated by r, i.e., $D(r) \equiv \{r' : r' \leq r\}$. We need to know which maps have Priestley duals which preserve this Heyting operation.

Lemma 4.8. *The morphisms $f : S \to R$ between finite posets whose Priestley duals preserve the Heyting operation are the monotone maps satisfying*

$$f(D(s)) = D(f(s))$$

for all $s \in S$. Such a map has a dual which is an embedding of finite Heyting algebras iff it is a surjection.

Proof. A proof may be recovered from the literature: by [6] the (complete) Heyting homomorphisms coincide with the open homomorphisms; by [2], open homomorphisms correspond under Ω to open maps $f : S \to R$ if (and only if) the space S is T_D; $f : (S, \leq) \to (R, \leq)$ is open in the Alexandroff topologies (they are always T_D) iff $f(D(s)) = D(f(s))$ for all $s \in S$.

We also offer a direct proof for the reader's convenience. Suppose that f^{-1} preserves $\to$, that $s \in S$, and that $r \leq f(s)$. Then

$$\begin{aligned} D(s) \cap f^{-1}(D(r)) \subseteq f^{1}(D(r) \setminus \{r\}) &\implies s \in f^{-1}(D(r)) \to f^{-1}(D(r) \setminus \{r\}) \\ &\implies s \in f^{-1}(D(r) \to (D(r) \setminus \{r\})) \\ &\implies f(s) \in D(r) \to (D(r) \setminus \{r\}) \\ &\implies D(f(s)) \cap D(r) \subseteq D(r) \setminus \{r\}. \end{aligned}$$

The first containment fails because the last one does (consider r), and this shows that $r = f(s')$ for some $s' \leq s$, which is to say that $D(f(s)) = f(D(s))$.

Now suppose $D(f(s)) = f(D(s))$ for all $s \in S$, and consider $U, V \in \mathcal{D}(R)$. That

$$f^{-1}(U \to V) \subseteq f^{-1}(U) \to f^{-1}(V)$$

follows from the fact that f^{-1} preserves intersections, so consider $s \in f^{-1}(U) \to f^{-1}(V)$, i.e., $D(s) \cap f^{-1}(U) \subseteq f^{-1}(V)$. We claim that $f(s) \in U \to V$, i.e., that $D(f(s)) \cap U \subseteq V$. For if $r \in D(f(s)) \cap U$ then, since $D(f(s)) = f(D(s))$, $r = f(s')$ for some $s' \leq s$. But then $s' \in D(s) \cap f^{-1}(U)$ hence $s' \in f^{-1}(V)$, meaning $r = f(s') \in V$. This proves the claim, and the claim shows that f^{-1} preserves $\to$.

Finally, f^{-1} is obviously one-to-one iff f is onto. □

For the rest of this article we suspend the convention that T is a a forest, and assume henceforth only that T is a finite poset.

Theorem 4.9. *Let T be a finite poset, and let $\mathcal{X}$ be the class of Priestley spaces X such that the Priestley dual of X is a Heyting lattice, and such that X contains no copy of T. Let $\mathcal{V}$ be the class of Heyting algebras with Priestley spaces (of the underlying lattices) in X. Then the following statements are equivalent.*

1. *T is a tree.*
2. *$\mathcal{V}$ is a subvariety of* **Hey** *determined by one extra equation in $\vee$ and $\to$.*
3. *$\mathcal{V}$ is a subquasivariety of* **Hey**, *i.e., $\mathcal{V}$ is closed under products and subobjects.*

Proof. The implication from (1) to (2) is Proposition 4.7, and from (2) to (3) is trivial. So assume (3) to prove (1). Since $\mathcal{V}$ is closed under products, $\mathcal{X}$ is closed under sums and hence T has to be connected. Now define $\tilde{T}$ as the set of all words $w = t_1 t_2 \ldots t_n$ in vertices t_i of T such that t_n is maximal and $t_i \prec t_{i+1}$ for all $i < n$. Order $\tilde{T}$ by declaring

$$w \leq w' \quad \text{iff} \quad w = w'' w' \text{for some } w''.$$

Define $f : \tilde{T} \to T$ by setting

$$f(t_1 \ldots t_n) = t_1.$$

Then

(a) f is monotone and onto,
(b) $f(D(w)) = D(f(w))$, and
(c) if $w \prec w'$ then w' is uniquely determined.

If $\tilde{L}$ and L are the Heyting algebras with Priestley spaces $\tilde{T}$ and T, we have L isomorphic to a subalgebra of $\tilde{L}$ by Lemma 4.8. Hence $\tilde{L} \notin \mathcal{V}$ since otherwise $L \in \mathcal{V}$ and $T \in \mathcal{X}$. Thus $\tilde{T}$ contains a copy of T, and by (c) and the connectedness we see that T is a tree. □

Restricting ourselves to the finite case we similarly obtain the following.

Theorem 4.10. *Let T be a finite poset, let $\mathcal{X}$ be the class of finite posets containing no copy of T, and let $\mathcal{V}$ be the class of Heyting algebras with Priestley duals (of the underlying lattices) lying in $\mathcal{X}$. Then the following statements are equivalent.*

1. *T is a tree.*
2. *$\mathcal{V}$ is the class of finite algebras of a subvariety $\mathcal{V}$ of* **Hey** *determined by one extra equation in $\vee$ and $\to$.*
3. *$\mathcal{V}$ is the class of finite algebras of a subquasivariety of* **Hey**.

5. Forests with a bottom point

The general problem we would like to solve is to find, for any finite poset T, a "nice" condition on a lattice L which is both necessary and sufficient to insure that $\mathcal{P}(L)$ admits no copy of T. In this section we make use of our techniques to provide a small step in the direction of the general problem by treating the case of a forest with one additional point at the bottom. The result is Theorem 5.6, and the reader may judge whether the condition on L which arises there is nice. However, this condition is not first order on its face, and we do not know if a first-order condition exists.

Throughout this section T designates a finite poset with least element t_0 such that $T' \equiv T \setminus \{t_0\}$ is a nonempty forest. We retain some of the notation used heretofore; for example, the map $a' : T \to L$ associated with the map $a : T \to L$ is still given by the rule

$$a'(t) = \bigvee_{t \nleq \tau} a(\tau).$$

Note in particular that $a'(t_0) = 0$, and that as before, a separates a copy $I : T \to \mathcal{I}(L)$ iff $a'(t) \in I(t)$ and $a(t) \notin I(t)$ for all $t \in T$. We must, however, modify slightly the notion of a T-supplement of a map $a : T \to L$.

Definition 5.1. Let $a : T \to L$ be any function. A *T-supplement of a* is a function $c : T \to L$ such that for all $t \in T'$,

$$a(t) \wedge c(t) \leq \bigvee_{\tau < t} c(\tau) \vee a'(t).$$

A *T-complement of a* is a T-supplement c for which $c(t) = 1$ for some $t \in \max(T)$. We let

$$F(a) \equiv \mathsf{Fltr}\{c(t_0) \wedge a(t_0) : c \text{ is a } T\text{-complement of } a\}.$$

The distinction between the two notions of T-supplement, i.e., between Definitions 3.6 and 5.1, is subtle. The crucial difference is that, although $c(t_0)$ appears on the right-hand-side of some of the inequalities displayed in Definition 5.1, it never appears on the left-hand-side of such an inequality. Thus these inequalities are explicitly of two types:

$$\begin{aligned} a(t) \wedge c(t) &\leq c(t_0) \vee a'(t), \quad t \in \min(T'), \\ a(t) \wedge c(t) &\leq \bigvee_{\tau \prec t} c(\tau) \vee a'(t), \quad t \in T' \setminus \min(T'). \end{aligned}$$

Lemma 5.2. *Let $x : T \to \mathcal{P}(L)$ be a copy and let $c : T \to L$ be a T-complement of a separator a of x. Then $c(t_0) \notin x(t_0)$.*

Proof. Put $S \equiv \{s \in T : c(s) \notin x(s)\}$. Since $c(t) = 1$ for some $t \in \max(T)$, we see that $t \in S \cap \max(T) \neq \emptyset$. And since for every $s \in S \cap T'$ we have $\bigvee_{\tau < s} c(\tau) \vee a'(s) \geq a(s) \wedge c(s) \notin x(s)$ and $a'(s) \in x(s)$, it follows that there is some $\tau < s$ such that $\tau \in S$. We conclude that $t_0 \in S$. □

Corollary 5.3. *If a separates a copy $x : T \to \mathcal{P}(L)$ then $F(a)$ is a proper filter.*

Proof. Since $c(t_0) \notin x(t_0)$ for any T-complement c of a by Lemma 5.6, and since $a(t_0) \notin x(t_0)$ by definition of separator, the generators of $F(a)$ all lie in the proper filter $L \setminus x(t_0)$. □

Proposition 5.4. *Suppose $a : T \to L$ is such that $F(a)$ is a proper filter. Then for any $I \in \mathcal{I}(L)$ such that $I \cap F(a) = \emptyset$ there is a copy $x : T \to L$ separated by a such that $I \subseteq x(t_0)$.*

Proof. First use Lemma 2.2(4) to find a point y in $\mathcal{P}(L)$ such that $I \subseteq y$ and $y \cap F(a) = \emptyset$. Then define $J : T' \to \mathcal{I}(L)$ inductively as follows.

- For $t \in \min(T')$, $J(t) \equiv (y, a'(t)) \downarrow a(t)$.
- For $t \in T' \setminus \min(T')$, $J(t) \equiv \left(\bigcup_{\tau \prec t} J(\tau), a'(t)\right) \downarrow a(t)$.

We claim that $J(t)$ is proper for all $t \in T'$. For if not, then because J is monotone there are elements $t \in \max(T)$ for which $J(t)$ is improper. In this case we can define a T-complement c for a as follows. For $t \in \max(T)$ choose $c(t)$ to be any member of $J(t)$, subject only to the proviso that $c(t)$ is chosen to be 1 whenever $J(t)$ contains 1. Suppose now that $c(t)$ has been defined for some $t \in T' \setminus \min(T')$ in such a way that $c(t) \in J(t)$. Since $J(t) = \left(\bigcup_{\tau \prec t} J(\tau), a'(t)\right) \downarrow a(t)$, there exist $c_\tau \in J(\tau)$, $\tau \prec t$, such that $a'(t) \vee \bigvee_{\tau \prec t} c_\tau \geq a(t) \wedge d(t)$. Put $c(\tau) \equiv c_\tau$ for $\tau \prec t$. Finally, suppose that $c(t)$ has been defined for all $t \in \min(T')$ in such a way that $c(t) \in J(t) = (y, a'(t)) \downarrow a(t)$, say $a(t) \wedge c(t) \leq b_t \vee a'(t)$ for $b_t \in y$. Define $c(t_0) \equiv \bigvee_{\min(T')} b_t \in y$. The resulting map $c : T \to L$ is clearly a T-complement for a

such that $c(t_0) \in y$, contrary to the hypothesis that $y \cap F(a) = \emptyset$. This contradiction establishes the claim that $J(t)$ is proper for all $t \in T'$.

The claim shows that $a(t) \notin J(t)$ for any $t \in T'$, since otherwise $J(t) = J(t) \downarrow a(t)$ would be improper. But then a separates J, since $a'(t) \in J(t)$ for any $t \in T'$ by construction. Proposition 3.1 then supplies a copy $x : T' \to \mathcal{P}(L)$ of T' separated by the restriction of a to T' such that $J(t) \subseteq x(t)$ for all $t \in T'$. If we simply extend this map to T by defining $x(t_0) \equiv y$, we get a copy $x : T \to \mathcal{P}(L)$ of T separated by a such that $I \subseteq y \subseteq x(t_0)$. That a separates this extension of x is because $a'(t_0) = 0 \in y = x(t_0)$ and $a(t_0) \notin y = x(t_0)$. □

Corollary 5.5. *Let $a : T \to L$ be a map and I an ideal on L. Then there is a copy $x : T \to L$ separated by a such that $I \subseteq x(t_0)$ iff $I \cap F(a) = \emptyset$.*

We come to the major result of this section.

Theorem 5.6. *$\mathcal{P}(L)$ admits no copy of T iff $F(a)$ is improper for every map $a : T \to L$.*

The definition of T-complement of a map $a : T \to L$ is certainly first order in the constants $a(t)$, $t \in T$. But the condition that $F(a)$ be improper is not first order on its face because there seems to be no intrinsic bound on the number of generators b which this filter requires.

We close with a simple application of Theorem 5.6.

Example 5.7. *Figure 1 shows the diamond $T = \{0, 1, 2, 3\}$.*

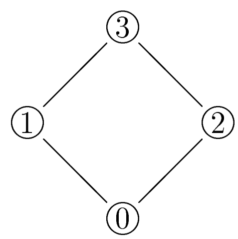

FIGURE 1. The diamond

Proposition 5.8. *$\mathcal{P}(L)$ contains no diamond iff*

$$F(a_1, a_2) \equiv \mathsf{Fltr}\{b : \exists c_1, c_2 \ (c_1 \vee c_2 = 1,\ c_1 \wedge a_1 \leq b \vee a_2,\ c_2 \wedge a_2 \leq b \vee a_1)\}$$

is an improper filter for every pair $a_1, a_2 \in L$.

Proof. Suppose $F(a_1, a_2)$ is proper for some $a_1, a_2 \in L$. Define $a : T \to L$ by setting $a(1) \equiv a_1$, $a(2) \equiv a_2$, $a_0 \equiv a_1 \wedge a_2$, and $a(3) \equiv 1$. We claim that $F(a) \subseteq F(a_1, a_2)$. To establish this claim, consider an arbitrary T-complement c of a. By definition of T-complement we have these inequalities.

$$\begin{aligned} a(3) \wedge c(3) &\leq c(1) \vee c(2) \vee a'(3) = c(1) \vee c(2) \vee a_1 \vee a_2 \\ a(2) \wedge c(2) &\leq c(0) \vee a'(2) = c(0) \vee a_1 \\ a(1) \wedge c(1) &\leq c(0) \vee a'(1) = c(0) \vee a_2 \end{aligned}$$

If we set $c_1 \equiv c(1) \vee a_2$, $c_2 \equiv c(2) \vee a_1$, and $b \equiv c(0)$, we get the inequalities which define b as a generator of $F(a_1, a_2)$. This shows that $c(0) \in F(a_1, a_2)$. Since it is clear that $a_1 \in F(a_1, a_2)$ (set $c_1 = 1$ and $c_2 = 0$) and that $a_2 \in F(a_1, a_2)$ likewise, we see that $a(0) \in F(a_1, a_2)$ and hence that $F(a) \subseteq F(a_1, a_2)$. Theorem 5.6 then produces a copy of T in $\mathcal{P}(L)$.

Now suppose that $\mathcal{P}(L)$ admits a copy of T. Then by Theorem 5.6 there is some $a : T \to L$ for which $F(a)$ is proper. Put $a_1 \equiv a(0) \vee a(1)$ and $a_2 \equiv a(0) \vee a(2)$. We claim that $F(a_1, a_2) \subseteq F(a)$. To verify this claim consider a generator b of $F(a_1, a_2)$, say c_1 and c_2 satisfy $c_1 \vee c_2 = 1$, $c_1 \wedge a_1 \leq b \vee a_2$, and $c_2 \wedge a_2 \leq b \vee a_1$. Define $c : T \to L$ by setting $c(0) \equiv b$, $c(1) \equiv c_1$, $c(2) \equiv c_2$, and $c(3) \equiv 1$. Then it is routine to verify that c is a T-complement of a, so that $b \geq c(0) \wedge a(0) \in F(a)$ hence $b \in F(a)$. This proves the claim and the proposition. □

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