

CONGRUENCES OF PARTIAL AND TOTAL ALGEBRAS

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1. INTRODUCTION

Section 2 gives a straight-forward proof that every finite lattice is the congruence lattice of a finite partial algebra. Bill Lampe [5] pointed out that this result has been known for a long time, and in Section 3 we give some background about closure operators and begin to develop the framework in which the original result was presented. We also recall a theorem from Berman's thesis that relates congruence lattices of partial algebras with those of total algebras.

This is a mash-up of notations, definitions, and theorems for the Universal Algebra and Lattice Theory Seminar in Hawaii, Fall Semester 2016. The notes are unfinished and far from perfect. Nonetheless, they might stimulate discussion in the seminar and elicit some criticism that we can use to improve them. So far most, if not all, of what appears below is known. See, for example, [1, 2, 3, 4].

2. A WELL KNOWN RESULT

In this section we give a straight-forward proof of the fact that every finite lattice is the congruence lattice of a finite partial algebra.

Lemma 2.1. *Let X be a finite set, and let $\text{Eq}(X)$ denote the lattice of equivalence relations on X . If $L \leq \text{Eq}(X)$ is a 0-1-sublattice, and $\rho \in \text{Eq}(X)$ and $\rho \notin L$, then for some $k < \omega$ there exists a partial operation $f: X^k \rightarrow X$ that is compatible with L and incompatible with ρ .*

Proof. First we focus on the relations in L that are above ρ . Let $\rho^\uparrow \cap L = \{\gamma \in L \mid \gamma \geq \rho\}$. Since $\rho \notin L$, we have $\gamma > \rho$ for all $\gamma \in \rho^\uparrow \cap L$. Now, $\rho^\uparrow \cap L$ has a least element $\rho^* = \bigwedge(\rho^\uparrow \cap L)$. Clearly $\rho^* \geq \rho$ and since $\rho^* \in L$ we have $\rho^* \neq \rho$, so $\rho^* > \rho$. Therefore, there exists $(u, v) \in \rho^* - \rho$.

Next consider the elements of L that are not above ρ . For each such $\alpha_i \in L - \rho^\uparrow$ there exists $(x_i, y_i) \in \rho - \alpha_i$. Let $(x_1, y_1), \dots, (x_k, y_k)$ be the list of all unique such pairs (i.e., each pair appears in the list exactly once). Define the partial function $f: X^k \rightarrow X$ at only two points of X^k ; specifically, let

$$f(x_1, \dots, x_k) = u \quad \text{and} \quad f(y_1, \dots, y_k) = v.$$

Then, since $(\forall i)(x_i, y_i) \in \rho$ and $(u, v) \notin \rho$, f is incompatible with ρ . On the other hand, $(u, v) \in \rho^* = \bigwedge(\rho^\uparrow \cap L)$, so $(u, v) \in \gamma$ for every $\gamma \in \rho^\uparrow \cap L$, so f is compatible with every $\gamma \in \rho^\uparrow \cap L$.

Finally, for each $\alpha_i \in L$ not above ρ there is at least one pair $(x_i, y_i) \notin \alpha_i$. Therefore, it is impossible for f to be incompatible with any such α_i . \square

Theorem 2.2. *Let X be a finite set and let $L \leq \text{Eq}(X)$ be a 0-1-sublattice. Then there exists a finite partial algebra $\mathbb{X} = \langle X, F \rangle$ with $\text{Con}(\mathbb{X}) = L$.*

Proof. By the lemma, for each $\rho \in \text{Eq}(X) - L$, there exists $k < \omega$ and $f_\rho: X^k \rightarrow X$ such that f_ρ is compatible with every relation in L and incompatible with ρ . Let \mathcal{R} be the set $\text{Eq}(X) - L$ of all equivalence relations on X that do not belong to L . Define, $F = \{f_\rho \mid \rho \in \mathcal{R}\}$. Evidently, $\text{Con}\langle X, F \rangle = L$. \square

3. CLOSURE SYSTEMS AND MOORE FAMILIES

3.1. Closure systems and operators. A **closure system** on a set X is a collection \mathcal{C} of subsets of X that is closed under arbitrary intersection (including the empty intersection, so $\bigcap \emptyset = X \in \mathcal{C}$). Thus a closure system is a complete meet semilattice with respect to subset inclusion ordering. Since every complete meet semilattice is automatically a complete lattice (see [6, Theorem 2.5]), the closed sets of a closure system form a complete lattice.

Examples of closure systems that are especially relevant for our work are the following:

- order ideals of an ordered set
- subalgebras of an algebra
- equivalence relations on a set
- congruence relations of an algebra

Let $\mathbf{P} = \langle P, \leq \rangle$ be a poset. An function $\mathbf{C}: P \rightarrow P$ is called a **closure operator** on \mathbf{P} if it satisfies the following axioms for all $x, y \in P$.

- (1) $x \leq \mathbf{C}x$ (extensivity)
- (2) $x \leq y$ implies $\mathbf{C}x \leq \mathbf{C}y$ (monotonicity)
- (3) $\mathbf{C}\mathbf{C}x = \mathbf{C}x$ (idempotence)

Thus, a closure operator is an extensive idempotent poset endomorphism, and the definition above is equivalent to the single axiom $(\forall x, y \in P)(x \leq \mathbf{C}y \iff \mathbf{C}x \leq \mathbf{C}y)$.

Example 3.1. Let X be a set and let $Y \subseteq X$. Define $\mathbf{C}_Y: \mathcal{P}(X) \rightarrow \mathcal{P}(X)$ by $\mathbf{C}_Y(W) = W \cup Y$. Then \mathbf{C}_Y is a closure operator on $\langle \mathcal{P}(X), \subseteq \rangle$.

A **fixed point** of a function $\mathbf{C}: P \rightarrow P$ is an $x \in P$ satisfying $\mathbf{C}x = x$. A fixed point of a closure operator is called **closed**. If the poset $\mathbf{P} = \langle P, \leq \rangle$ happens to be a complete lattice, then by extensivity the largest element $\top = \bigvee P$ is a fixed point of every closure operator on \mathbf{P} . Also, the collection of fixed points of a closure operator is closed under arbitrary meets. (Proof: If \mathcal{A} is a set of fixed points of \mathbf{C} and $a \in \mathcal{A}$, then $\bigwedge \mathcal{A} \leq a$, so by monotonicity $\mathbf{C}(\bigwedge \mathcal{A}) \leq \mathbf{C}a = a$. Since a was arbitrary, $\mathbf{C}(\bigwedge \mathcal{A}) \leq \bigwedge \mathcal{A}$. By extensivity, $\bigwedge \mathcal{A} \leq \mathbf{C}(\bigwedge \mathcal{A})$. Therefore, $\mathbf{C}(\bigwedge \mathcal{A}) = \bigwedge \mathcal{A}$.) The set of closure operators on \mathbf{P} themselves form a complete lattice under the pointwise order: $\mathbf{C}_1 \leq \mathbf{C}_2$ iff $\mathbf{C}_1 x \leq \mathbf{C}_2 x$ for all $x \in P$.

Some of these observations can be restated as follows: if $\mathbf{P} = \langle P, \leq \rangle$ is a complete lattice, then the set $\mathcal{C} \subseteq P$ of fixed points of a closure operator is a **Moore family** on \mathbf{P} —that is, $\bigvee P \in \mathcal{C}$ and every nonempty subset of \mathcal{C} is closed under arbitrary meets.

Conversely, if we are given a Moore family \mathcal{C} on \mathbf{P} , and if we define $\mathbf{C}: P \rightarrow P$ by

$$\mathbf{C}a = \bigwedge \{b \in \mathcal{C} \mid a \leq b\},$$

then \mathbf{C} satisfies conditions (1)–(3) above, making it a closure operator. To summarize, $\mathcal{C} \subseteq P$ is the set of fixed points (i.e., closed elements) of a closure operator on \mathbf{P} if and only if \mathcal{C} is a Moore family on \mathbf{P} .

Every Moore family on \mathbf{P} is itself the universe of a complete lattice with the order inherited from \mathbf{P} , though the join may differ from the join of \mathbf{P} .

3.1.1. More Moore families. The name “closure system” is typically reserved for the special case in which \mathbf{P} happens to be the powerset Boolean algebra of a set X —that is, $\mathbf{P} = \langle \mathcal{P}(X), \subseteq \rangle$; in that case, a Moore family on \mathbf{P} is called a closure system on X .

Example 3.2. Let X be a set, let $\mathbf{R}(X) = \bigcup_{n < \omega} \mathcal{P}(X^n)$ be the set of all finitary relations on X , and let $\mathbf{O}(X) = \bigcup_{n < \omega} X^{X^n}$ be the set of all finitary operations on X . Define $F: \mathcal{P}(\mathbf{R}(X)) \rightarrow \mathcal{P}(\mathbf{O}(X))$ and $G: \mathcal{P}(\mathbf{O}(X)) \rightarrow \mathcal{P}(\mathbf{R}(X))$ as follows: if $A \subseteq \mathbf{R}(X)$ and $B \subseteq \mathbf{O}(X)$, then

$$F(A) = \{f \in \mathbf{O}(X) \mid f \text{ is compatible with every relation in } A\},$$

$$G(B) = \{\rho \in \mathbf{R}(X) \mid \rho \text{ is compatible with every operation in } B\}.$$

Then $G \circ F$ is a closure operator on the lattice of all relations on X .

Example 3.3. Let X be a set, let $\text{Eq}(X)$ denote the lattice of equivalence relations on X , and let X^X be the set of all unary operations on X . Define $F_1: \mathcal{P}(\text{Eq}(X)) \rightarrow \mathcal{P}(X^X)$ and $G_1: \mathcal{P}(X^X) \rightarrow \mathcal{P}(\text{Eq}(X))$ as follows: if $A \subseteq \text{Eq}(X)$ and $B \subseteq X^X$, then

$$F_1(A) = \{f \in X^X \mid f \text{ is compatible with every relation in } A\},$$

$$G_1(B) = \{\rho \in \text{Eq}(X) \mid \rho \text{ is compatible with every operation in } B\}.$$

Then $G_1 \circ F_1$ is a closure operator on the lattice $\text{Eq}(X)$ of all equivalence relations on X .

Example 3.4 (Pudlák-Tůma [7]). Let $\mathbf{L} = \langle L, \vee, \wedge \rangle$ be a lattice, $u, v \in L$, and $u \leq v$. Define a subset $L_{u,v}$ of L by $L_{u,v} = \{x \in L \mid v \leq x \text{ or } u \not\leq x\}$. The partial order relation of the lattice \mathbf{L} induces a lattice order on $L_{u,v}$. Denote the resulting lattice by $\mathbf{L}_{u,v}$. Then the meet of $\mathbf{L}_{u,v}$ is that of \mathbf{L} , whereas the join of $\mathbf{L}_{u,v}$ is

$$x \vee_{u,v} y = \begin{cases} x \vee y, & \text{if } u \not\leq x \vee y, \\ x \vee y \vee v, & \text{if } u \leq x \vee y. \end{cases}$$

Define a mapping $\sigma_{u,v}: L \rightarrow L_{u,v}$ as follows:

$$\sigma_{u,v}(x) = \begin{cases} x, & \text{if } u \not\leq x, \\ x \vee v, & \text{if } u \leq x. \end{cases}$$

Then $\sigma_{u,v}$ is a surjective join-homomorphism. In fact, every join-homomorphism $\phi: L \rightarrow K$ satisfying $\phi(u) = \phi(v)$ splits as $\phi = \psi \circ \sigma_{u,v}$ for some $\psi: L_{u,v} \rightarrow K$. (See the commutative diagram in Figure 1.) As a mapping from \mathbf{L} to itself, $\sigma_{u,v}$ does not preserve joins. However, $\sigma_{u,v}: L \rightarrow L$ is a closure operator and $L_{u,v}$ is the set of fixed points of $\sigma_{u,v}$ (the closed sets).

4. ALGEBRAIC CLOSURE SYSTEMS

A subset D of an ordered set P is called **up-directed** if for every $x, y \in D$ there exists $z \in D$ such that $x \leq z$ and $y \leq z$. A closure operator $\mathbf{C}: \mathcal{P}(X) \rightarrow \mathcal{P}(X)$ is called **algebraic** provided, for all $A \subseteq X$,

$$\mathbf{C}A = \bigcup \{\mathbf{C}F \mid F \subseteq A \text{ and } F \text{ finite}\}.$$

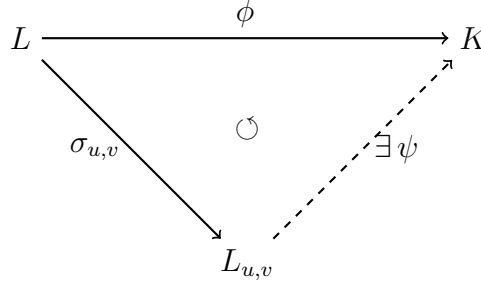


FIGURE 1. Every join-homomorphism collapsing u and v is divisible by $\sigma_{u,v}$.

The collection \mathcal{C} of closed sets of an algebraic closure operator is called an **algebraic closure system**.

Theorem 4.1 (cf. [6] Thm 3.1). *Let \mathcal{C} be the closure system of fixed points of the closure operator $\mathbf{C}: \mathcal{P}(X) \rightarrow \mathcal{P}(X)$. The following are equivalent:*

- (1) \mathbf{C} is an algebraic closure operator
- (2) \mathcal{C} is an algebraic closure system
- (3) If $D \subseteq \mathcal{C}$ is up-directed and $C \subseteq D$ is a chain, then $\bigcup C$ is closed.
- (4) If $D \subseteq \mathcal{C}$ is up-directed, then $\bigcup D$ is closed.
- (5) If $C \subseteq \mathcal{C}$ is a chain, then $\bigcup C$ is closed.

4.1. Algebraic closure systems are subalgebra lattices. For an algebra \mathbf{A} , the subalgebra generation operator $\text{Sg}^{\mathbf{A}}$ is an algebraic closure operator (on the poset $\langle \mathcal{P}(A), \subseteq \rangle$) whose fixed points are the subalgebras of \mathbf{A} . Thus the lattice $\langle \text{Sub}(\mathbf{A}), \vee, \wedge \rangle$ of subalgebras of \mathbf{A} is an algebraic closure system. Conversely, given an algebraic closure system \mathcal{S} , we can construct an algebra $\mathbf{A} = \langle A, F \rangle$ so that $\mathcal{S} = \text{Sub}(\mathbf{A})$. Here is how: let $\mathbf{C}_{\mathcal{S}}$ denote the corresponding closure operator. For each $a_0, a_1, \dots, a_{n-1}, b \in A$ such that $b \in \mathbf{C}_{\mathcal{S}}(\{a_0, a_1, \dots, a_{n-1}\})$, define the n -ary operation $f_{\mathbf{a},b}$ so that $f_{\mathbf{a},b}(a_0, a_1, \dots, a_{n-1}) = b$ and for all other tuples $f_{\mathbf{a},b}(c_0, c_1, \dots, c_{n-1}) = c_0$. Then define

$$F = \{f_{\mathbf{a},b} \mid n < \omega, \mathbf{a} \in A^n, b \in \mathbf{C}_{\mathcal{S}} \mathbf{a}\}.$$

Every subalgebra is the union of its finitely generated subsubalgebras... *(to be continued)*

4.2. Congruence lattices. Start with an algebraic closure system \mathcal{S} of equivalence relations on a set A and let $\mathbf{C}_{\mathcal{S}}$ be the associated closure operator. Let $(a_0, b_0), (a_1, b_1), \dots, (a_{n-1}, b_{n-1})$, and (c_0, c_1) belong to $A \times A$, and suppose $(c_0, c_1) \in \mathbf{C}_{\mathcal{S}}(\{(a_0, b_0), (a_1, b_1), \dots, (a_{n-1}, b_{n-1})\})$. Define $f_{\mathbf{a},\mathbf{b},\mathbf{c}}: (A \times A)^n \rightarrow A \times A$ so that $f_{\mathbf{a},\mathbf{b},\mathbf{c}}((a_0, b_0), (a_1, b_1), \dots, (a_{n-1}, b_{n-1})) = (c_0, c_1)$. Do this for each triple $\mathbf{a}, \mathbf{b}, \mathbf{c}$... *(to be continued)*

5. STRONG CONGRUENCE RELATIONS

We use bold letters like \mathbf{x} to denote tuples like (x_0, \dots, x_{n-1}) , where the value n will be clear from context. Let θ be an equivalence relation on a set A and suppose $f: A^n \rightarrow A$ is a partial function. We call θ and f

- **weakly compatible** provided that, for all $(a_i, b_i) \in \theta$, if $f(\mathbf{a})$ and $f(\mathbf{b})$ are both defined, then $f(\mathbf{a}) \theta f(\mathbf{b})$.

- **strongly compatible** provided that, for all $(a_i, b_i) \in \theta$, if $f(\mathbf{a})$ is defined, then $f(\mathbf{b})$ is defined and $f(\mathbf{a}) \theta f(\mathbf{b})$.

Let $\mathbb{A} = \langle A, F \rangle$ be a partial algebra and θ an equivalence relation on A . We call θ a **strong** (resp., **weak**) **congruence** of \mathbb{A} if θ is strongly (resp., weakly) compatible with every $f \in F$. Denote by $\text{Cons}(\mathbb{A})$ (resp., $\text{Con}_{\mathbf{W}}(\mathbb{A})$) the set of strong (resp., weak) congruences of \mathbb{A} .

Here are some elementary observations about strong and weak congruences. (See Berman's thesis [1] and paper [2] for more details and proofs.) If $\mathbb{A} = \langle A, F \rangle$ is a partial algebra then the set $\text{Cons}(\mathbb{A})$ of strong congruence relations of \mathbb{A} forms a sublattice of $\text{Eq}(A)$. The set $\text{Con}_{\mathbf{W}}(\mathbb{A})$ of weak congruences also forms a lattice, but it is not a sublattice of $\text{Eq}(A)$ since there may be pairs of relations whose join in $\text{Eq}(A)$ is strictly below their join in $\text{Con}_{\mathbf{W}}(\mathbb{A})$. We will see examples below.

A *total algebra*—an algebra for which all operations are defined everywhere—is a special case of a partial algebra. In case a partial algebra is not total, we may refer to it as a *proper partial algebra*. This simply means that there is at least one operation that is not defined everywhere. It should be obvious that for total algebras strong and weak congruences reduce to the usual definition of congruence relation on an algebra. In particular, if \mathbb{A} is total, then the largest strong congruence of \mathbb{A} is $1_A := A \times A$.

The converse of the last sentence in the previous paragraph is also true. That is, if the largest strong congruence of \mathbb{A} is 1_A , then \mathbb{A} is total. To see this, suppose $f \in F$ is an n -ary partial operation and denote by $\text{dom}(f)$ the subset of A^n on which f is defined. Let θ be a strong congruence of \mathbb{A} . Then the following implication holds:

$$(a_0, a_1, \dots, a_{n-1}) \in \text{dom}(f) \implies [a_0]_{\theta} \times [a_1]_{\theta} \times \dots \times [a_{n-1}]_{\theta} \subseteq \text{dom}(f).$$

That is, if f is defined at an n -tuple, then f must also be defined on the whole Cartesian product of θ -blocks containing the coordinates of that tuple. In particular, if 1_A is a strong congruence of \mathbb{A} , then every operation of \mathbb{A} must be total, while if $\mathbb{A} = \langle A, F \rangle$ is a *proper partial algebra*, then the largest strong congruence of \mathbb{A} must be strictly below 1_A .

To summarize, \mathbb{A} is a total algebra iff $\bigvee \text{Cons}(\mathbb{A}) = 1_A$.

Theorem 5.1 (Berman's Thesis [1] Thm 1.18). *Let \mathbb{A} be a finite partial algebra and $\text{Cons}(\mathbb{A})$ the lattice of strong congruence relations of \mathbb{A} . Then there exists a finite algebra \mathbf{A} such that $\text{Con}(\mathbf{A}) = \text{Cons}(\mathbb{A})$.*

Remarks.

- (1) Either one or both of the algebras in Theorem 5.1 can be taken to be unary.
- (2) It follows easily from Theorem 5.1 that the class of lattices isomorphic to strong congruence lattices of finite partial algebras is equal to the class of lattices isomorphic to congruence lattices of finite partial algebras. (This is [1, Thm 1.19].)

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