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ORTHORINGS

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Abstract

Certain ring-like structures, so-called orthorings, are introduced which are in a natural one-to-one correspondence with lattices with 0 every principal ideal of which is an ortholattice. This correspondence generalizes the well-known bijection between Boolean rings and Boolean algebras. It turns out that orthorings have nice congruence and ideal properties.

Keywords: ortholattice, generalized ortholattice, sectionally complemented lattice, orthoring, arithmetical variety, weakly regular variety, congruence kernel, ideal term, basis of ideal terms, subtractive term.

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1. Introduction

The well-known natural bijective correspondence between Boolean algebras and Boolean rings is widely used in applications, see [1] for details. This correspondence was generalized in different ways thus giving rise to natural connections between certain lattice structures on the one hand and certain ring-like structures on the other hand. On the lattice-theoretical side the following structures were considered: orthomodular lattices ([8] and [18]), ortholattices ([2]), bounded lattices with an involutory antiautomorphism ([9], [10], [11], [12], [13] and [14]), pseudocomplemented semilattices ([5]) and MV-algebras ([6]). The corresponding ring-like structures were called orthomodular Boolean quasirings or orhomodular pseudorings, orthopseudorings, orthopseudosemirings, Boolean quasirings and pseudorings, respectively. (No name was assigned to the ring-like structures induced by pseudocomplemented semilattices.) In [3] the ring-like structures introduced in [2] and [9], respectively, are related to each other. However, each one of the derived ring-like structures considered so far in this context was endowed with a constant 1 which plays a role similar to the unit element in rings. On the other hand, starting with so-called generalized Boolean algebras, one can derive Boolean rings which need not have a unit element (see [1]). A similar approach was used in [7], where so-called generalized orthomodular lattices (introduced by M.F. Janowitz in [17], see also [16]) were considered. Our aim is to investigate ring-like structures (so-called orthorings) which correspond to lattices with 0 such that every principal lattice ideal is an ortholattice. It should be pointed out that though these lattices do not form a variety, the term equivalent orthorings form a variety and hence allow the application of universal algebraic methods and results. Moreover, we are going to show that – in spite of their generality – orthorings have nice properties.

We recall that an *ortholattice* is an algebra $(L;\vee,\wedge,',0,1)$ of type $(2,2,1,0,0)$ such that $(L;\vee,\wedge,0,1)$ is a bounded lattice and $(x')'=x$, $(x\vee y)'=x'\wedge y'$, $(x\wedge y)'=x'\vee y'$, $x\vee x'=1$ and $x\wedge x'=0$ for all $x,y\in L$.

2. Orthorings

First we introduce the concept of a generalized ortholattice and distinguish generalized ortholattices from other classes of lattices.

Definition 2.1. (cf., e.g., [15]). A lattice $(L; \vee, \wedge, 0)$ with 0 is called a *sectionally complemented lattice* if for each $a \in L$, $([0, a]; \vee, \wedge)$ is a complemented lattice, i.e. for every $a, b \in L$ with $b \leq a$ there exists an element c of L with $c \leq a$, $b \vee c = a$ and $b \wedge c = 0$.

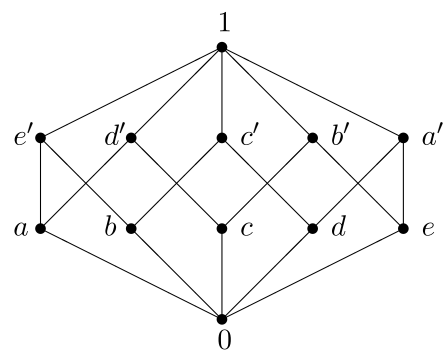
Definition 2.2. $(L; \vee, \wedge, ({}^a\, ; a \in L), 0)$ where $(L; \vee, \wedge, 0)$ is a lattice with 0 is called a *generalized ortholattice* if for each $a \in L$, $([0, a]; \vee, \wedge, {}^a, 0, a)$ is an ortholattice.

Of course, if $(L; \vee, \wedge, ({}^a\, ; a \in L), 0)$ is a generalized ortholattice, then $(L; \vee, \wedge, 0)$ is a sectionally complemented lattice.

Example 2.1. The five-element modular non-distributive lattice is sectionally complemented but it cannot be considered as a generalized ortholattice since it has an odd number of elements.

Example 2.2. If $(L; \vee, \wedge, ', 0, 1)$ is an orthomodular lattice, i.e. an ortholattice satisfying $y = x \vee (y \wedge x')$ for all $x, y \in L$ with $x \leq y$, then $(L; \vee, \wedge, (x \mapsto x' \wedge a; a \in L), 0)$ is a generalized ortholattice.

Example 2.3. The following Hasse diagram shows a non-orthomodular generalized ortholattice:



Next we introduce ring-like structures corresponding to generalized ortholattices.

Definition 2.3. An *orthoring* is an algebra $(R; +, \cdot, 0)$ of type $(2, 2, 0)$ satisfying

(O1) $x + y = y + x$,

(O2) $x + 0 = x$,

(O3) $xy = yx$,

(O4) $(xy)z = x(yz)$,

(O5) $xx = x$,

(O6) $x0 = 0$,

(O7) $(xy + x) + x = xy$,

(O8) $((x + y) + xy) + xy = x + y$,

(O9) $(xy + x)x = xy + x$,

(O10) $(x + y)xy = 0$,

(O11) $((x + y) + xy)x = x$,

(O12) $((xy + xz) + xyz)x = (xy + xz) + xyz$

and

(O13) $(xyz + x)(xy + x) = xy + x$.

Remark 2.1. Orthorings $\mathcal{R} = (R; +, \cdot, 0)$ are of characteristic 2, i.e. $x+x = 0$ for all $x \in R$.

Proof.

$$x + x \overset{(O1),(O2)}{=} (0 + x) + x \overset{(O4),(O10)}{=} ((x + x)xx + x) + x \overset{(O3)-(O5)}{=}$$

$$\overset{(O3)-(O5)}{=} (x(x + x) + x) + x \overset{(O7)}{=} x(x + x) \overset{(O3)-(O5)}{=} (x + x)xx \overset{(O10)}{=} 0.$$

■

Now we can state our main result describing a natural bijective correspondence between generalized ortholattices and orthorings.

Theorem 2.1. *For fixed set L the formulas*

$$x + y := (x \wedge y)^{x \vee y},$$

$$xy := x \wedge y$$

and

$$x \vee y := (x + y) + xy,$$
$$x \wedge y := xy,$$
$$x^y := x + y$$

induce mutually inverse bijections between the set of all generalized ortholattices on L and the set of all orthorings on L.

Proof. Let $\mathcal{L} = (L; \vee, \wedge, ({}^a\,;\, a \in L), 0)$ be a generalized ortholattice and put $x + y := (x \wedge y)^{x \vee y}$ and $xy := x \wedge y$ for all $x, y \in L$. Let $x, y, z \in L$. Then

$$(x + y) + xy = ((x \wedge y)^{x \vee y} \wedge x \wedge y)^{(x \wedge y)^{x \vee y} \vee (x \wedge y)} = 0^{x \vee y} = x \vee y,$$
$$x + 0 = 0^x = x,$$
$$(xy + x) + x = ((x \wedge y)^x)^x = x \wedge y = xy,$$
$$((x + y) + xy) + xy = (x \wedge y)^{x \vee y} = x + y,$$
$$(xy + x)x = (x \wedge y)^x \wedge x = (x \wedge y)^x = xy + x,$$
$$(x + y)xy = (x \wedge y)^{x \vee y} \wedge x \wedge y = 0,$$
$$((x + y) + xy)x = (x \vee y) \wedge x = x,$$
$$((xy + xz) + xyz)x = ((xy + xz) + (xy)(xz))x = ((x \wedge y) \vee (x \wedge z)) \wedge x =$$
$$= (x \wedge y) \vee (x \wedge z) = (xy + xz) + (xy)(xz) = (xy + xz) + xyz \text{ and}$$
$$(xyz + x)(xy + x) = (x \wedge y \wedge z)^x \wedge (x \wedge y)^x = (x \wedge y)^x = xy + x.$$

Hence, $(L; +, \cdot, 0)$ is an orthoring. Moreover,

$$(x + y) + xy = x \vee y,$$
$$xy = x \wedge y$$

and

$$x \leq y \text{ implies } x + y = x^y.$$

Therefore, the algebra induced by $(L;+,\cdot,0)$ according to the formulas given in the theorem coincides with $\mathcal{L}$.

Conversely, let $\mathcal{R}=(L;+,\cdot,0)$ be an orthoring and put $x\vee y:=(x+y)+xy$, $x\wedge y:=xy$ and $x^y:=x+y$ for all $x,y\in L$. Let $(L;\leq)$ denote the poset corresponding to the meet-semilattice $(L;\cdot)$ and $x,y,z\in L$. Then

$$x(x\vee y)=x((x+y)+xy)\overset{(O3)}{=}((x+y)+xy)x\overset{(O11)}{=}x,\ \text{i.e. } x\leq x\vee y,$$

$$y(x\vee y)=y((x+y)+xy)\overset{(O1),(O3)}{=}((y+x)+yx)y\overset{(O11)}{=}y,\ \text{i.e. } y\leq x\vee y,$$

$$x,y\leq z \text{ implies } (x\vee y)z=((x+y)+xy)z\overset{(O3),(O4)}{=}((zx+zy)+zxy)z$$
$$\overset{(O4),(O12)}{=}(zx+zy)+zxy\overset{(O3),(O4)}{=}(x+y)+xy=x\vee y,\ \text{i.e. } x\vee y\leq z,$$

$$x\leq y \text{ implies } x^y y=(x+y)y\overset{(O3)}{=}(yx+y)y\overset{(O9)}{=}yx+y\overset{(O3)}{=}x+y=x^y,$$
$$\text{i.e. } x^y\leq y,$$

$$x\leq y \text{ implies } (x^y)^y=(x+y)+y\overset{(O3)}{=}(yx+y)+y\overset{(O7)}{=}yx\overset{(O3)}{=}x,$$

$$x\leq y\leq z \text{ implies } y^z x^z=(y+z)(x+z)\overset{(O3),(O4)}{=}(zyx+z)(zy+z)$$
$$\overset{(O4),(O13)}{=}zy+z\overset{(O3)}{=}y+z=y^z,\ \text{i.e. } y^z\leq x^z \text{ and}$$

$$x\leq y \text{ implies } x\wedge x^y=x(x+y)\overset{(O3),(O4)}{=}(x+y)xy\overset{(O10)}{=}0.$$

Hence $(L;\vee,\wedge,({}^a;\, a\in L),0)$ is a generalized ortholattice. Moreover,

$$(x\wedge y)^{x\vee y}=xy+((x+y)+xy)\overset{(O1)}{=}((x+y)+xy)+xy\overset{(O8)}{=}x+y \text{ and}$$
$$x\wedge y=xy.$$

This shows that the algebra induced by $(L;\vee,\wedge,({}^a;\, a\in L),0)$ according to the formulas of the theorem coincides with $\mathcal{R}$. ∎

Remark 2.2. If $(L; \vee, \wedge, ', 0, 1)$ is a Boolean algebra, then $x+y = (x \wedge y)^{x \vee y}$ is the well-known symmetric difference since $(x \wedge y') \vee (x' \wedge y) = (x \wedge y)' \wedge (x \vee y) = (x \wedge y)^{x \vee y}$ for all $x, y \in L$.

Comparing the definition of an orthoring to the definition of a Boolean pseudoring introduced in [7] and comparing the definition of a generalized ortholattice with that of a generalized orthomodular lattice (cf. [17]), we obtain

Theorem 2.2. *An orthoring* $(R; +, \cdot, 0)$ *is a Boolean pseudoring if and only if* $(x + y)x = x + xy$ *and* $(xyz + x)y = xyz + xy$ *for all* $x, y, z \in R$. *A generalized ortholattice* $(L; \vee, \wedge, (^a; a \in L), 0)$ *is a generalized orthomodular lattice if and only if* $x^z \wedge y = x^y$ *for all* $x, y, z \in L$ *with* $x \leq y \leq z$.

Proof. The second assertion can be proved as follows: Let $\mathcal{L} = (L; \vee, \wedge, (^a\,; a \in L), 0)$ be a generalized ortholattice. If $\mathcal{L}$ is a generalized orthomodular lattice, then $x^z \wedge y = x^y$ for all $x, y, z \in L$ with $x \leq y \leq z$ according to the definition of a generalized orthomodular lattice. Conversely, if $x^z \wedge y = x^y$ for all $x, y, z \in L$ with $x \leq y \leq z$, then $x \vee (y \wedge x^z) = x \vee x^y = y$ for all $x, y, z \in L$ with $x \leq y \leq z$ and, hence, $([0, z]; \vee, \wedge, ^z, 0, z)$ is orthomodular for all $z \in L$. Therefore, $\mathcal{L}$ is a generalized orthomodular lattice. ∎

3. Congruence and ideal properties

For an overview on congruence conditions, their characterizations and the theory of ideals in universal algebras, see [4].

A variety is called *arithmetical* if it is both congruence permutable and congruence distributive. A variety with a constant term 0 is called *weakly regular* if any congruence of an algebra belonging to this variety is determined by its 0-class.

It is easy to see that the congruence lattice of an orthoring is a sublattice of the congruence lattice of the corresponding sectionally complemented lattice. Since it is well known that sectionally complemented lattices are arithmetical and weakly regular (see, e.g., [15]), this carries over to orthorings.

Here we will provide a different (and direct) proof of this result.

Theorem 3.1. *Orthorings are arithmetical and weakly regular.*

Proof. Consider the terms

$$\begin{aligned}
t_1(x,y) &:= xy + x,\\
t_2(x,y) &:= xy + y,\\
t(x,y,z,u) &:= (y+u) + z \text{ and}\\
m(x,y,z) &:= (xy + yz) + zx.
\end{aligned}$$

We show that t_1, t_2 and t satisfy the identities

$$\begin{aligned}
&t_1(x,x) = t_2(x,x) = 0,\\
&t(x,y,t_1(x,y),t_2(x,y)) = x \text{ and}\\
&t(x,y,0,0) = y
\end{aligned}$$

from which it follows that orthorings are permutable and weakly regular according to Theorem 6.4.11 of [4]. Moreover, we prove that m is a majority term, i.e. it satisfies

$$m(x,x,y) = m(x,y,x) = m(y,x,x) = x$$

from which we obtain that ortholattices are congruence distributive according to Corollary 3.2.4 of [4].

The following calculations yield the desired identities:

$$(x + xy) + xy = ((x \wedge y)^x \wedge (x \wedge y))^{(x\wedge y)^x \vee (x \wedge y)} = 0^x = x,$$

$$t_1(x,x) = xx + x \overset{\text{(O5)}}{=} x + x = 0,$$

$$t_2(x,x) = xx + x \overset{\text{(O5)}}{=} x + x = 0,$$

$$\begin{aligned}
&t(x,y,t_1(x,y),t_2(x,y)) = (y + (xy + y)) + (xy + x) \overset{\text{(O1),(O3)}}{=}\\
&\quad \overset{\text{(O1),(O3)}}{=} ((yx + y) + y) + (xy + x) \overset{\text{(O7)}}{=} yx + (xy + x) \overset{\text{(O1),(O3)}}{=}\\
&\quad \overset{\text{(O1),(O3)}}{=} (x + xy) + xy = x,
\end{aligned}$$

$$t(x,y,0,0) = (y+0)+0 \overset{(O2)}{=} y,$$

$$m(x,x,y) = (xx+xy)+yx \overset{(O3),(O5)}{=} (x+xy)+xy = x,$$

$$m(x,y,x) = (xy+yx)+xx \overset{(O3),(O5)}{=} (xy+xy)+x \overset{(O1),(O2)}{=} x \text{ and}$$

$$m(y,x,x) = (yx+xx)+xy \overset{(O1),(O3),(O5)}{=} (x+xy)+xy = x.$$

■

Let $\mathcal{V}$ be a variety with a constant term 0, $\mathcal{A}$ an algebra belonging to $\mathcal{V}$ and B a subset of the carrier set of $\mathcal{A}$. A term $t(x_1,\dots,x_n)$ is called an *ideal term* with respect to the variables $x_i, i \in I$, $(I \subseteq \{1,\dots,n\})$ if $t(x_1,\dots,x_n) = 0$ whenever $x_i = 0$ for all $i \in I$. Let $t(x_1,\dots,x_n)$ be an ideal term with respect to the variables $x_i, i \in I$. B is called *closed with respect to* t if $t(a_1,\dots,a_n) \in B$ provided $a_1,\dots,a_n \in A$ and $a_i \in B$ for all $i \in I$. B is called an *ideal* of $\mathcal{A}$ if B is closed with respect to all ideal terms. A set T of ideal terms is called a *basis of ideal terms* if a subset of the carrier set of an algebra $\mathcal{C}$ belonging to $\mathcal{V}$ is an ideal of $\mathcal{C}$ whenever it is closed with respect to all ideal terms belonging to T. If Θ is a congruence on $\mathcal{A}$, then the congruence class $[0]\Theta$ of 0 with respect to Θ is called the *conguence kernel* of Θ. It is easy to see that every congruence kernel is an ideal. If $\mathcal{V}$ has a so-called *subtractive term*, i.e. a binary term s satisfying $s(x,0) = x$ and $s(x,x) = 0$, then, conversely, every ideal is a congruence kernel (cf. Theorems 6.6.11 and 10.1.10 of [4]). This is the case with orthorings, because the term $s(x,y) := x+y$ serves as a subtractive term.

Ideals in orthorings can now be characterized as follows:

Theorem 3.2. *A subset I of the base set R of an orthoring $\mathcal{R}$ containing 0 is an ideal of $\mathcal{R}$ if and only if $x,y,z,u \in R$ and $xy+x, xy+y, zu+z, zu+u \in I$ together imply $(x+z)(y+u)+(x+z), xyzu+xz \in I$.*

Proof. This follows from Theorem 10.3.1 of [4] by using the terms introduced in the proof of Theorem 3.1. ■

Corollary 3.1. *Every ideal I of an orthoring $\mathcal{R} = (R;+,\cdot,0)$ is the kernel of the congruence $\Theta_I := \{(x,y) \in R \times R \mid xy+x \in I$ and $xy+y \in I\}$ on $\mathcal{R}$.*

Proof. It is almost evident that I is the kernel of Θ_I where Θ_I is reflexive and compatible. However, the variety of orthorings is congruence permutable according to Theorem 3.1, and by [19], every compatible reflexive relation on $\mathcal{R}$ is a congruence on $\mathcal{R}$ (see also Corollary 3.1.13 in [4]). ∎

Finally, we present a finite basis of ideal terms for orthorings:

Theorem 3.3. *The following terms form a basis of ideal terms for orthorings:*

$0,$

$(((x+y_1)+y_2)+((z+y_3)+y_4))(x+z)+(((x+y_1)+y_2)+((z+y_3)+y_4)),$

$(((x+y_1)+y_2)+((z+y_3)+y_4))(x+z)+(x+z),$

$((x+y_1)+y_2)((z+y_3)+y_4)xz+((x+y_1)+y_2)((z+y_3)+y_4),$

$((x+y_1)+y_2)((z+y_3)+y_4)xz+xz,$

and

$y_1+y_2.$

Proof. This follows from Theorem 10.3.4 of [4] by using the terms introduced in the proof of Theorem 3.1. ∎

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