Distributive Quasigroups of Size 243

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Medial Quasigroups

Definition

A groupoid $(Q, \cdot)$ is called *medial* if it satisfies

$$(x \cdot y) \cdot (z \cdot u) = (x \cdot z) \cdot (y \cdot u).$$

Theorem (K. Toyoda; R. Bruck)

A groupoid $(Q, \cdot)$ is a medial quasigroup if and only if there exist

- *an abelian group $(Q, +, 0)$,*
- *two commuting automorphisms $\varphi, \psi \in \mathrm{Aut}(Q, +)$,*
- *a constant $c \in Q$,*

such that, for each $x, y \in Q$,

$$x \cdot y = \varphi(x) + \psi(y) + c.$$

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Trimedial Quasigroups

Definition

A groupoid $(Q, \cdot)$ is called *trimedial* if every 3-generated sub-groupoid is medial

Theorem (T. Kepka)

A groupoid $(Q, \cdot)$ is a tri-medial quasigroup if and only if there exist

- *a commutative Moufang loop $(Q, +, 0)$,*
- *two commuting 1-central automorphisms $\varphi, \psi \in \mathrm{Aut}(Q, +)$,*
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Moufang Loops

Definition

Let $(Q,+)$ be a quasigroup. Then Q is a *loop* if there exists a neutral element 0 in Q.

Definition

A loop $(Q,+,0)$ is called a *Moufang loop* if it satisfies

$$x\cdot(y\cdot(x\cdot z))=((x\cdot y)\cdot x)\cdot z.$$

Definition

The center of a loop Q is the set

$$Z(Q)=\{a\in Q;\ ax=xa,\ a\cdot xy=ax\cdot y,\ x\cdot ay=xa\cdot y,\ xy\cdot a=x\cdot ya;\ \forall x,y\in Q\}$$

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Commutative Moufang Loops

Definition

Let Q be a loop and let $\alpha : Q \to Q$. We denote by $\hat{\alpha}$ the mapping $x \mapsto x + \alpha(x)$.
We say that α is 1-central, if $\hat{\alpha}(x) \in Z(Q)$, for all $x \in Q$.

Proposition (R. Bruck)

Let $(Q, +, 0)$ be a commutative Moufang loop. Then $3Q \subseteq Z(Q)$.

Corollary

Let Q be a finite commutative Moufang loop. If $|Q|$ is coprime to 3 then Q is an abelian group.

Example

The mapping $x \mapsto 2x$ is a 1-central automorphism of a commutative Moufang loop.

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Theorem (V. D. Belousov)

A quasigroup is distributive if and only if it is idempotent and trimedial.

Corollary (V. D. Belousov; J.-P. Soublin)

A groupoid $(Q,\cdot)$ is a distributive quasigroup iff there exist

- *a commutative Moufang loop $(Q,+,0)$,*
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Decomposition of Finite Distributive Quasigroups

Theorem (B. Fisher, J. D. H. Smith)

Let Q be a finite distributive quasigroup. Then

$$Q \cong Q_1 \times \cdots \times Q_k$$

where $|Q_i| = p_i^{n_i}$, for some prime p_i.
Moreover, if, for some $i \leqslant k$, Q_i is not medial then $p_i = 3$.

Theorem (T. Kepka, P. Němec)

There are 6 non-medial distributive quasigroups of size 81, up to isomorphism.

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1-central Automorphisms

Lemma (P.J., D.S., P.V.)

Let Q be a commutative Moufang loop. A mapping $\alpha : Q \to Q$ is a 1-central automorphism if and only if $\hat{\alpha}$ is a fix-point-free endomorphism $Q \to Z(Q)$.
Moreover, the endomorphism $id - \alpha$ is a bijection if and only if $\hat{\alpha}(x) = 2x$ implies $x = 0$.

Corollary

A groupoid $(Q, \cdot)$ is a distributive quasigroup iff there exist

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Isomorphism of Distributive Quasigroups

Proposition

Let Q_1 and Q_2 be commutative Moufang loops and let $\hat{\psi}_i : Q_i \to Z(Q_i)$ be endomorphism, for $i \in \{1,2\}$. The associated distributive quasigroups are isomorphic if and only if there exists an isomorphism $f : Q_1 \to Q_2$ such that

$$\hat{\psi}_1 = f^{-1} \circ \hat{\psi}_2 \circ f.$$

Enumeration of Distributive Quasigroups of Size 243

Theorem (T. Kepka, P. Němec)

There exist 6 non-associative commutative Moufang loops of order 243.

Theorem (P.J., D.S., P.V.)

There exist 92 non-medial distributive quasigroups of order 243.

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Example of a Distributive Quasigroup of Size 243

Fact (H. Zassenhaus)

The set $\mathbb{Z}_3^5$ *with the operation*

$$(a_1,b_1,c_1,d_1,e_1)+(a_2,b_2,c_2,d_2,e_2)=$$
$$(a_1+a_2+(e_1+e_2)\cdot(c_1d_2-d_1c_2),b_1+b_2,c_1+c_2,d_1+d_2,e_1+e_2)$$

is a non-associative CML of order 243 and exponent 3.

Proposition (P.J., D.S., P.V.)

Up to conjugacy, there are six endomorphisms $\hat{\psi}: Q \to Z(Q)$ *satisfying* $\hat{\psi}(x) \notin \{x, 2x\}$*, for all* $x \neq 0$*:*

$$(a,b,c,d,e)\mapsto(0,0,0,0,0) \qquad (a,b,c,d,e)\mapsto(b,0,0,0,0)$$
$$(a,b,c,d,e)\mapsto(c,0,0,0,0) \qquad (a,b,c,d,e)\mapsto(0,c,0,0,0)$$
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Steiner and Mendelsohn Distributive Quasigroups

Proposition (D. Donovan, T. Griggs, T. McCourt, J. Opršal, D. Stanovský)

A distributive quasigroup $(Q,\cdot)$ satisfies

$$x\cdot(y\cdot x)=y$$

if and only if $\hat{\psi}^2-3\hat{\psi}+3x=0$. Such a quasigroup is called distributive Mendelsohn quasigroup.
Moreover, Q is also commutative if and only if $(Q,+)$ is of exponent 3 and $\hat{\psi}=0$. Such quasigroups are called distributive Steiner quasigroups.

Proposition (P.J., D.S., P.V.)

There are 6 non-medial Mendelsohn quasigroups of order 243, one of them being Steiner.

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