

AXIOMATIZATION OF QUASIGROUPS

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Abstract

Quasigroups were originally described combinatorially, in terms of existence and uniqueness conditions on the solutions to certain equations. Evans introduced a universal-algebraic characterization, as algebras with three binary operations satisfying four identities. Now, quasigroups are redefined as heterogeneous algebras, satisfying just two conditions respectively known as hypercommutativity and hypercancellativity.

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1. INTRODUCTION

Quasigroups are one of the oldest topics in algebra and combinatorics, dating back at least to Euler [1]. Evans [2] showed how they could be defined in universal-algebraic fashion, using three binary operations and four identities. Nevertheless, this definition does not seem entirely satisfactory for such a fundamental object of mathematics, since it requires an explicit listing of the four apparently related identities. A new definition is presented in the current paper, using heterogeneous algebras known as *hyperquasigroups*. With this new definition, just two identities are needed: *hypercommutativity* and *hypercancellativity*.

The original combinatorial and equational definitions of quasigroups are recalled in Section 2. Section 3 introduces the higher level of a hyperquasigroup, a structure known as a *reflexion-inversion space*. Various examples of such spaces are discussed. Hyperquasigroups themselves are defined in Section 4. Section 5 then exhibits hyperquasigroups embodying each of the types of reflexion-inversion space presented in Section 3. In particular (Proposition 5.2), each quasigroup is part of a hyperquasigroup with the symmetric group S_3 on three symbols as the corresponding reflexion-inversion space. In the converse direction, Section 6 shows that each hyperquasigroup comprises a set equipped with disjoint sets of mutually conjugate quasigroup operations.

2. QUASIGROUPS

A quasigroup Q was first understood as a set equipped with a binary multiplication, denoted by \cdot or mere juxtaposition, such that in the equation

$$x \cdot y = z ,$$

knowledge of any two of x, y, z specifies the third uniquely. To make a distinction with subsequent concepts, it is convenient to describe a quasigroup in this original sense as a *combinatorial quasigroup* (Q, \cdot) .

For each element q of a set Q with a binary multiplication denoted by \cdot or juxtaposition, a *left multiplication* $L_Q(q)$ or

$$L(q) : Q \rightarrow Q; x \mapsto qx$$

and *right multiplication* $R_Q(q)$ or

$$R(q) : Q \rightarrow Q; x \mapsto xq$$

are obtained from the binary multiplication by the process of ‘‘Currying,’’ the usual trick for reducing a function of two arguments (in this case the multiplication) to a parametrized family of functions of a single argument (compare [6]). If (Q, \cdot) is a quasigroup, then the right and left multiplications are bijections of the underlying set Q . Indeed, the bijectivity of $L_Q(q)$ and $R_Q(q)$ for each element q of Q is equivalent with (Q, \cdot) being a quasigroup.

Unfortunately, the combinatorial definition of a quasigroup is unsuitable for most algebraic purposes: A surjective multiplicative homomorphism $f : (Q, \cdot) \rightarrow (P, \cdot)$ whose domain is a combinatorial quasigroup (Q, \cdot) may

have an image (P, \cdot) which is not a combinatorial quasigroup (compare [6, Example I.2.2.1], for instance). To circumvent this problem, Evans [2] redefined quasigroups as *equational quasigroups*, sets $(Q, \cdot, /, \backslash)$ equipped with three binary operations of multiplication, *right division* $/$ and *left division* \backslash , satisfying the identities:

$$(IL) \quad x \backslash (x \cdot y) = y;$$

$$(IR) \quad y = (y \cdot x) / x;$$

$$(SL) \quad x \cdot (x \backslash y) = y;$$

$$(SR) \quad y = (y / x) \cdot x.$$

Note that (IL), (IR) give the respective injectivity of the left and right multiplications, while (SL), (SR) give their surjectivity. Thus an equational quasigroup $(Q, \cdot, /, \backslash)$ yields a combinatorial quasigroup (Q, \cdot) . Conversely, a combinatorial quasigroup (Q, \cdot) yields an equational quasigroup $(Q, \cdot, /, \backslash)$ with $x / y = xR(y)^{-1}$ and $x \backslash y = yL(x)^{-1}$.

In an equational quasigroup $(Q, \cdot, /, \backslash)$, the three equations

$$(2.1) \quad x_1 \cdot x_2 = x_3, \quad x_3 / x_2 = x_1, \quad x_1 \backslash x_3 = x_2$$

are equivalent. Introducing the opposite operations

$$x \circ y = y \cdot x, \quad x // y = y / x, \quad x \backslash \backslash y = y \backslash x$$

on Q , the equations (2.1) are further equivalent to the equations

$$x_2 \circ x_1 = x_3, \quad x_2 // x_3 = x_1, \quad x_3 \backslash \backslash x_1 = x_2.$$

Thus each of

$$(2.2) \quad (Q, \cdot), \quad (Q, /), \quad (Q, \backslash), \quad (Q, \circ), \quad (Q, //), \quad (Q, \backslash \backslash)$$

is a (combinatorial) quasigroup. In particular, note that the identities (IR) in (Q, \backslash) and (IL) in $(Q, /)$ yield the respective identities

$$(DL) \quad x / (y \backslash x) = y,$$

$$(DR) \quad y = (x / y) \backslash x$$

in the basic quasigroup divisions. The six quasigroups (2.2) are known as the *conjugates*, “parastrophes” [4, p. 43] [5] or “derived quasigroups” [3] of (Q, \cdot) .

3. REFLEXION-INVERSION SPACES

Hyperquasigroups, as defined in Section 4 below, consist of structure at three levels, amounting to a two-sorted algebra (compare Remarks 3.2 and 4.2). The second (higher-level) sort is given in this section as follows.

Definition 3.1. A *reflexion-inversion space* (G, σ, τ) is a set G equipped with two involutive actions, a *reflexion*

$$(3.1) \quad \sigma : G \rightarrow G; g \mapsto \sigma g$$

and an *inversion*

$$(3.2) \quad \tau : G \rightarrow G; g \mapsto \tau g.$$

The involutivity of the actions means that

$$\sigma\sigma g = g \quad \text{and} \quad \tau\tau g = g$$

for each point g of the reflexion-inversion space.

Remark 3.2. Let H be the free product of two copies $\langle \sigma \rangle$ and $\langle \tau \rangle$ of the group of order two. The underlying set of this group is the set of (possibly empty) words in the two-letter alphabet $\{\sigma, \tau\}$ having no consecutive letters repeated. The product is given by the juxtaposition of words, followed by cancellation of repeated pairs of letters. For example, $\tau\sigma \cdot \sigma\tau\sigma\tau = \sigma\tau$. Inversion in the group just reverses the words, for example $(\sigma\tau\sigma\tau)^{-1} = \tau\sigma\tau\sigma$. A reflexion-inversion space (G, σ, τ) as in Definition 3.1 may then be interpreted as a left H -set with actions specified by (3.1) and (3.2). It is nevertheless important to note that reflexion-inversion spaces are richer than H -sets, since their structure includes the choice of the specific involutions σ and τ .

The remainder of the section presents some typical examples of reflexion-inversion spaces that may form part of a hyperquasigroup structure. The first example serves to motivate the terminology of Definition 3.1.

Example 3.3. Let F be a field. Let G be the complement $F \setminus \{0, 1\}$ of the set $\{0, 1\}$ in F . Define

$$\sigma : G \rightarrow G; g \mapsto 1 - g$$

and

$$\tau : G \rightarrow G; g \mapsto g^{-1}.$$

Then (G, σ, τ) forms a reflexion-inversion space. Note that the abstract inversion τ is a literal inversion in this case. If F is the field of real or complex numbers, then the abstract reflexion σ is literal reflexion in the point $1/2$.

Example 3.4. Let G be a group containing two elements σ and τ with $\sigma^2 = \tau^2 = 1$. Then G forms a reflexion-inversion space in which the reflexion and inversion are the respective left multiplications by σ and τ .

Example 3.5. Let $\mathbb{C}/2\pi i\mathbb{Z}$ denote the quotient of the set of complex numbers by the equivalence relation

$$\{(z, z') \in \mathbb{C}^2 \mid z - z' \in 2\pi i\mathbb{Z}\}.$$

It is also convenient to identify each equivalence class in the set $\mathbb{C}/2\pi i\mathbb{Z}$ with its unique representative element in the fundamental domain

$$\{x + iy \in \mathbb{C} \mid x \in \mathbb{R}, y \in [0, 2\pi) \subset \mathbb{R}\}.$$

Let $G = (\mathbb{C}/2\pi i\mathbb{Z})^2$. (Topologically, this space is the product $T^2 \times \mathbb{R}^2$ of a torus with a plane.) Define

$$\sigma : G \rightarrow G; (a, b) \mapsto (b, a)$$

and

$$\tau : G \rightarrow G; (a, b) \mapsto (i\pi + a - b, -b).$$

Then G forms a reflexion-inversion space.

Example 3.6. Let n be an even number, and let $G = (\mathbb{Z}/n\mathbb{Z})^2$. Define

$$\sigma : G \rightarrow G; (a, b) \mapsto (b, a)$$

and

$$\tau : G \rightarrow G; (a, b) \mapsto (a - b + n/2, -b).$$

Then G forms a reflexion-inversion space.

Example 3.7. Let A be an abelian group, and let $G = A^2$. Define

$$\sigma : G \rightarrow G; (a, b) \mapsto (b, a)$$

and

$$\tau : G \rightarrow G; (a, b) \mapsto (a - b, -b).$$

Then G forms a reflexion-inversion space in which the reflexion and inversion are linear maps.

4. HYPERQUASIGROUPS

Basing on the concept of a reflexion-inversion space, the definition of a hyperquasigroup may now be given.

Definition 4.1. A *hyperquasigroup* (Q, G) is a pair consisting of a set Q and a reflexion-inversion space G , together with a binary operation

$$Q^2 \times G \rightarrow Q; (x, y, g) \mapsto xy \underline{g}$$

of G on Q , such that the *hypercommutative law*

$$(4.1) \quad xy \underline{\sigma g} = yx \underline{g}$$

and the *hypercancellation law*

$$(4.2) \quad x(xy \underline{g}) \underline{\tau g} = y$$

are satisfied for all x, y in Q and g in G .

Remark 4.2. A hyperquasigroup may be interpreted as a two-sorted algebra (Q, G) . Here G is a left H -set according to Remark 3.2. The set G then acts on Q as in Definition 4.1.

Remark 4.3. The prefix “hyper-” in Definition 4.1 reflects the substitution of variables at both levels in (4.1) and (4.2), comparable to the substitution at both the argument and the operator level in hyperidentities [7].

Hypercommutativity is straightforward. The meaning of hypercancellativity is given by the following.

Proposition 4.4. *Let (Q, G) be a hyperquasigroup. For each element g of G , define*

$$(4.3) \quad \widehat{g} : Q^2 \rightarrow Q^2; (x, y) \mapsto (x, xy \underline{g}).$$

Then in the monoid of all self-maps on Q^2 , the element $\widehat{\tau g}$ is the inverse of \widehat{g} .

Proof. For x, y in Q , one has

$$(x, y) \xrightarrow{\widehat{g}} (x, xy \underline{g}) \xrightarrow{\widehat{\tau g}} (x, x(xy \underline{g}) \underline{\tau g}) = (x, y)$$

with the equality holding directly by the hypercancellativity (4.2). Similarly, one has

$$(x, y) \xrightarrow{\widehat{\tau g}} (x, xy \underline{\tau g}) \xrightarrow{\widehat{g}} (x, x(xy \underline{\tau g}) \underline{g}) = (x, y),$$

the equality here resulting from the hypercancellation equation (4.2) with g replaced by τg . Thus $\widehat{\tau g}$ is indeed the inverse of \widehat{g} . ■

5. CONSTRUCTIONS

For each of the examples of a reflexion-inversion space given in Section 3, one obtains corresponding constructions of hyperquasigroups.

Proposition 5.1. *Let Q be a vector space over a field F . Let G be the reflexion-inversion space of Example 3.3. Then a hyperquasigroup structure (Q, G) is defined by the action*

$$xy \underline{g} = x(1 - g) + yg$$

for x, y in Q and g in G .

Proof. The hypercommutativity and hypercancellativity may be verified directly. Certainly one has

$$xy \underline{\sigma g} = x(1 - (1 - g)) + y(1 - g) = y(1 - g) + xg = yx \underline{g},$$

the hypercommutativity. Then

$$\begin{aligned} x(xy \underline{g}) \underline{\tau g} &= x(1 - g^{-1}) + (x(1 - g) + yg)g^{-1} \\ &= x(1 - g^{-1}) + x(g^{-1} - 1) + y = y, \end{aligned}$$

as required for the hypercancellativity. ■

Proposition 5.2. *Let $(Q, \cdot, /, \backslash)$ be an equational quasigroup, and let G be the symmetric group S_3 on the three-element set $\{1, 2, 3\}$. Interpret G as a reflexion-inversion space according to Example 3.4, with reflexion $\sigma = (12)$ and inversion $\tau = (23)$. Then (Q, G) becomes a hyperquasigroup under the operations*

$$xy \underline{\perp} = x \cdot y, \quad xy \underline{\sigma\tau\sigma} = x/y, \quad xy \underline{\tau} = x \backslash y,$$

$$xy \underline{\sigma} = y \cdot x, \quad xy \underline{\tau\sigma} = y/x, \quad xy \underline{\sigma\tau} = y \backslash x.$$

Proof. The hypercommutativity is immediate from the definitions, while the hypercancellativity results from the identities (XL) and (XR) for $X = I, S, D$. Specifically, these identities take the following form:

$$(IL) : \quad y = x (xy \underline{\perp}) \underline{\tau}$$

$$(SL) : \quad y = x (xy \underline{\tau}) \underline{\perp}$$

$$(IR) : \quad y = x (xy \underline{\sigma}) \underline{\tau\sigma}$$

$$(SR) : \quad y = x (xy \underline{\tau\sigma}) \underline{\sigma}$$

$$(DL) : \quad y = x (xy \underline{\sigma\tau}) \underline{\tau\sigma\tau}$$

$$(DL) : \quad y = x (xy \underline{\tau\sigma\tau}) \underline{\sigma\tau}$$

(recalling the equation $\sigma\tau\sigma = \tau\sigma\tau$ in S_3). Thus the hypercancellativity (4.2) is explicitly verified for each of the six elements g of G . ■

Proposition 5.3. *Let Q be a complex vector space, and let G be the reflexion-inversion space of Example 3.5. Then a hyperquasigroup structure (Q, G) is defined by the action*

$$(5.1) \quad xy \underline{(a, b)} = xe^a + ye^b$$

for x, y in Q and (a, b) in G .

Proof. The hypercommutativity is immediate, while

$$\begin{aligned} x (xy \underline{(a, b)}) \underline{\tau(a, b)} &= xe^{i\pi+a-b} + (xe^a + ye^b)e^{-b} \\ &= -xe^{a-b} + xe^{a-b} + y = y \end{aligned}$$

gives the hypercancellativity. ■

The two remaining constructions offer discrete versions of Proposition 5.3 – note the formal similarity between the corresponding hyperquasigroup actions (5.1), (5.2) and (5.3).

Proposition 5.4. *Let R be a unital ring. For an even number n , let e be a root in R of the polynomial $X^{n/2} + 1$. Let Q be a unital right module over R , and let G be the reflexion-inversion space of Example 3.6. Then a hyperquasigroup structure (Q, G) is defined by the action*

$$(5.2) \quad xy(\underline{a}, b) = xe^a + ye^b$$

for x, y in Q and (a, b) in G .

Proof. Since $e^n = 1$, the action (5.2) is well-defined. The hypercommutativity is clear, while

$$\begin{aligned} x(xy(\underline{a}, b))\tau(\underline{a}, b) &= xe^{a-b+n/2} + (xe^a + ye^b)e^{-b} \\ &= -xe^{a-b} + xe^{a-b} + y = y \end{aligned}$$

gives the hypercancellativity. ■

Proposition 5.5. *Let e be an invertible element of a unital ring R of characteristic 2. Let Q be a unital right module over R , and let G be the reflexion-inversion space of Example 3.7 for the abelian group $A = \mathbb{Z}$. Then a hyperquasigroup structure (Q, G) is defined by the action*

$$(5.3) \quad xy(\underline{a}, b) = xe^a + ye^b$$

for x, y in Q and (a, b) in G .

Proof. Since e is invertible, the action (5.3) is well-defined. Hypercommutativity is immediate as usual, while

$$\begin{aligned} x(xy(\underline{a}, b))\tau(\underline{a}, b) &= xe^{a-b} + (xe^a + ye^b)e^{-b} \\ &= xe^{a-b} + xe^{a-b} + y = y \end{aligned}$$

gives the hypercancellativity. ■

6. FROM HYPERQUASIGROUPS TO QUASIGROUPS

According to Proposition 5.2, each quasigroup yields a hyperquasigroup. Here, it is shown that the converse is true: Hyperquasigroups yield combinatorial and equational quasigroups.

Theorem 6.1. *Let (Q, G) be a hyperquasigroup. Then for each element g of the reflexion-inversion space G , there is an equational quasigroup $(Q, \underline{\sigma g}, \underline{\sigma \tau g}, \underline{\tau \sigma g})$.*

Proof. It will be shown directly that $(Q, \underline{\sigma g}, \underline{\sigma \tau g}, \underline{\tau \sigma g})$ satisfies the four identities specifying equational quasigroups.

(IL): Replacing g with σg in the hypercancellativity equation (4.2) gives

$$y = x(xy \underline{\sigma g}) \underline{\tau \sigma g},$$

which is exactly the identity (IL) for $(Q, \underline{\sigma g}, \underline{\sigma \tau g}, \underline{\tau \sigma g})$.

(IR): The hypercancellativity equation (4.2) directly gives

$$y = x(xy \underline{g}) \underline{\tau g},$$

Using hypercommutativity, this may be rewritten as

$$y = (yx \underline{\sigma g}) x \underline{\sigma \tau g},$$

which is the identity (IR) for $(Q, \underline{\sigma g}, \underline{\sigma \tau g}, \underline{\tau \sigma g})$.

(SL): Replacing g with $\tau \sigma g$ in the hypercancellativity equation (4.2) gives

$$y = x(xy \underline{\tau \sigma g}) \underline{\sigma g},$$

which is the identity (SL) for $(Q, \underline{\sigma g}, \underline{\sigma \tau g}, \underline{\tau \sigma g})$.

(SR): Replacing g with τg in the hypercancellativity equation (4.2) gives

$$y = x(xy \underline{\tau g}) \underline{g}.$$

Using hypercommutativity, this may be rewritten as

$$y = (yx \underline{\sigma \tau g}) x \underline{\sigma g},$$

which is the identity (SR) for $(Q, \underline{\sigma g}, \underline{\sigma \tau g}, \underline{\tau \sigma g})$. ■

Corollary 6.2. *Let (Q, G) be a hyperquasigroup. Then for each element g of the reflexion-inversion space G , there is a combinatorial quasigroup (Q, \underline{g}) .*

Proof. Replace g by σg in the statement of Theorem 6.1. ■

Remark 6.3. In [3], James gave a characterization of combinatorial quasigroups that amounts to the invertibility of the maps \widehat{g} and $\widehat{\sigma g}$ in (4.3). James' characterization could be used as an alternative direct approach to the proof of Corollary 6.2.

Example 6.4. For a finite field F of order q , consider the hyperquasigroup (Q, G) given by Proposition 5.1. Here, the combinatorial quasigroups of Corollary 6.2 constitute a set of $q - 2$ mutually orthogonal idempotent and entropic quasigroups.

Example 6.5. For a fixed (combinatorial) quasigroup (Q, \cdot) , consider the hyperquasigroup (Q, S_3) given by Proposition 5.2. In this case, the combinatorial quasigroups of Corollary 6.2 form the full set of conjugates of (Q, \cdot) .

As a consequence of the following result, it will transpire that the situation of Example 6.5 is quite typical.

Proposition 6.6. *Let (Q, G) be a hyperquasigroup. Then for all x, y in Q and g in G , one has*

$$(6.1) \quad xy \underline{\sigma\tau\sigma g} = xy \underline{\tau\sigma\tau g}.$$

Proof. Consider the equational quasigroup $(Q, \underline{\sigma g}, \underline{\sigma\tau g}, \underline{\tau\sigma g})$ given by Theorem 6.1. The identity (DL) in this equational quasigroup takes the form

$$y = x (yx \underline{\tau\sigma g}) \underline{\sigma\tau g},$$

which may be rewritten as

$$(6.2) \quad y = x (xy \underline{\sigma\tau\sigma g}) \underline{\sigma\tau g}$$

using hypercommutativity. On the other hand, the hypercancellation equation (4.2) with g replaced by $\tau\sigma\tau g$ yields

$$(6.3) \quad y = x (xy \underline{\tau\sigma\tau g}) \underline{\sigma\tau g}.$$

Since $(Q, \underline{\sigma\tau g})$ is a combinatorial quasigroup (in which the equation $y = xz \underline{\sigma\tau g}$ has a unique solution z for given x and y), (6.2) and (6.3) together yield the desired result (6.1). ■

For a hyperquasigroup (Q, G) , consider the algebra (Q, \underline{G}) , the underlying set Q endowed with the set $\underline{G} = \{\underline{g} \mid g \in G\}$ of binary operations. The action of the involutions σ and τ on the reflexion-inversion space G yields an action on the binary operation set \underline{G} . Proposition 6.6 shows that the action of σ and τ on \underline{G} is an S_3 -action. For each element g of G , the elements \underline{g}' of the orbit $\underline{S_3g}$ of \underline{g} under this S_3 -action form the full set of quasigroup operations conjugate to the combinatorial quasigroup operation \underline{g} on Q . One may summarize as follows.

Theorem 6.7. *Each hyperquasigroup (Q, G) yields an algebra structure (Q, \underline{G}) consisting of the union*

$$\underline{G} = \bigcup_{g \in G} \underline{S_3g}$$

of mutually disjoint sets of conjugate quasigroup operations.

Between them, Proposition 5.2 and Theorem 6.7 give a complete description of the relationship between quasigroups and hyperquasigroups.

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