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# Orthogonal designs of order 32 and 64 via computational algebra

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## Abstract

Baumert and Hall describe a Williamson array construction based on quaternions. We extend by analogy this construction to larger arrays, using the multiplication table of the Cayley-Dickson algebras of dimensions 32 and 64. Then we use Gröbner bases to obtain full orthogonal designs of order 32 with 10 variables and of order 64 in 10 and 11 variables. Finally we use  $\text{OD}(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)$  to search for inequivalent Hadamard matrices of orders 96, 160, 224, 288. Such structured matrices are needed in Statistics and Coding Theory applications. This algebraic approach can be extended to larger orders, i.e.  $2^n, n \geq 7$ , provided that the structural properties of the corresponding polynomial ideals and their Gröbner bases are further investigated and understood.

## 1 Introduction

**Definition** Let  $x_1, \dots, x_t$  be commuting indeterminates. An orthogonal design  $X$  of order  $n$  and type  $(s_1, \dots, s_t)$  denoted  $\text{OD}(n; s_1, \dots, s_t)$ , where  $s_1, \dots, s_t$  are positive integers, is a matrix  $X$  of order  $n$  with entries from  $\{0, \pm x_1, \dots, \pm x_t\}$ , such that

$$XX^t = \left( \sum_{i=1}^t s_i x_i^2 \right) I_n,$$

where  $X^t$  denotes the transpose of  $X$  and  $I_n$  denotes the identity matrix of order  $n$ . For applications of ODs to wireless communications see [18] and the references

therein. For more details on orthogonal designs see the book [10] and the survey paper [17].

This paper is organized as follows. First we give an account of the classical Williamson construction for Hadamard matrices, from the point of view of quaternions, following Baumert and Hall. Then we show how the application of the Cayley-Dickson process on the algebra of sedenions, can be used to describe a full orthogonal design of order 32 with 10 variables. We use Gröbner bases [4] [5], [19] to locate a canonical solution of a system of equations that gives the orthogonal design of order 32. The multiplication table of the algebra of dimension 32 is used to construct right multiplication matrices which are used to form orthogonal designs. Using the right multiplication operator is a way to overcome the obstacle of non-associativity of the algebra. Non-associativity is an obstacle, because it is incompatible with the existence of matrix representations, that we could use directly to construct orthogonal designs. To circumvent this obstacle we use the right multiplication operator, as it seems that left multiplication is not suitable for our purposes. We apply this method to construct some full orthogonal designs of order 64 as well. In the last sections of the paper, we use the full orthogonal design of order 32 with 10 variables, to search for inequivalent Hadamard matrices of orders 96, 160, 224, 288. Inequivalent Hadamard matrices with a certain structure, in this case coming from orthogonal designs, are needed in Statistics and Coding Theory applications.

The Cayley-Dickson process in conjunction with Gröbner bases, provides a unifying algebraic framework for the construction of orthogonal designs of orders 32 and 64 with many variables. This approach can be extended to larger orders, i.e.  $2^n$ ,  $n \geq 7$ , provided that the structural properties of the corresponding polynomial ideals and their Gröbner bases are better understood.

## 2 Orthogonal designs of order 32 and 64 via Cayley-Dickson algebras

Baumert and Hall specify in [2, 3] how to construct the Williamson array via quaternions, see also [11].

The Cayley-Dickson process allows us to obtain an algebra of dimension  $2n$  from an algebra of dimension  $n$ , see [8, 13]. By applying the Cayley-Dickson process successively to the real numbers, one obtains the algebras of quaternions, octonions and sedenions.

The construction by Baumert and Hall can be repeated using octonions and sedenions instead of quaternions. This has been done in [14]. The corresponding orthogonal designs have been found to yield Hadamard matrices.

By applying the Cayley-Dickson process to the algebra of sedenions, one obtains a Cayley-Dickson algebra of dimension 32 with basis  $e_0 = 1, e_1, \dots, e_{31}$  whose multiplication table is omitted.

To associate a  $32 \times 32$  matrix to each basis element, we use the right multiplication operator, on the column vector

$$v = [ 1 \quad e_1 \quad \dots \quad e_{31} ]^t.$$

Then the thirty-two right multiplications

$$v \cdot e_0, v \cdot e_1, \dots, v \cdot e_{31},$$

give rise to thirty-two  $32 \times 32$  matrices  $q_0, \dots, q_{31}$ . Let  $A_1, \dots, A_{32}$  be commuting indeterminates. Then the sum  $A = \sum_{i=0}^{31} A_{i+1}q_i$  is equal to a  $32 \times 32$  array with the property that the diagonal elements of  $AA^t$  are all equal to  $\sum_{i=1}^{32} A_i^2$ , but whose other elements are not necessarily all zero. By requiring that all elements of  $AA^t$  (except the diagonal ones) are equal to zero, we obtain 252 equations in 30 variables (all variables except  $A_1, A_{17}$ ).

The reduced Gröbner basis (for a total degree reverse lexicographical ordering) of these 252 equations has 290 elements. The computation was done in Magma V2.11-2. Among the elements in the Gröbner basis, we are interested in the 105 binomials, which can be written concisely as:

$$A_{16-j}A_i - A_{i-16}A_{32-j}, i = 32 - j + 1, \dots, 32, j = 1, \dots, 14. \tag{1}$$

For each value of  $j$ , there are  $j$  binomials, which makes a total of  $\sum_{j=1}^{14} j = 105$  binomials. For  $j = 1$  the one binomial is equal to  $A_{15}A_{32} - A_{16}A_{31}$ . For  $j = 2$  the two binomials are equal to  $A_{14}A_{31} - A_{15}A_{30}, A_{14}A_{32} - A_{16}A_{30}$ .

Each solution of the 105 equations corresponding to the 105 binomials (1) can be completed to a solution of all the 290 equations coming from the Gröbner basis and thus yield a  $32 \times 32$  orthogonal design. The structure of these 105 binomials equations points out to the following canonical solution:

$$\begin{aligned} A_{18} = A_2, A_{19} = A_3, A_{20} = A_4, A_{21} = A_5, A_{22} = A_6, A_{23} = A_7, A_{24} = A_8, A_{25} = A_9, \\ A_{26} = A_{10}, A_{27} = A_{11}, A_{28} = A_{12}, A_{29} = A_{13}, A_{30} = A_{14}, A_{31} = A_{15}, A_{32} = A_{16} \end{aligned} \tag{2}$$

that can be completed to a solution of the 290 equations by requiring in addition that:

$$A_{10} = A_2, A_{11} = A_3, A_{12} = A_4, A_{13} = A_5, A_{14} = A_6, A_{15} = A_7, A_{16} = A_8. \tag{3}$$

The solution of the 290 equations, comprised of (2) and (3) gives rise to the 10-variable full orthogonal design  $OD(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)$  (where we have used the change of variables  $A1 = A, A2 = B, A3 = C, A4 = D, A5 = E, A6 = F, A7 = G, A8 = H, A9 = I, A17 = J$  to save space) given in the appendix.

Note that when we take the product of  $OD(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)$  with its transpose, the result is:

$$(A^2 + 4B^2 + 4C^2 + 4D^2 + 4E^2 + 4F^2 + 4G^2 + 4H^2 + 2I^2 + J^2)I_{32} \tag{4}$$

A full orthogonal design  $OD(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)$  has been found in [10] by a doubling construction on the full orthogonal design of order 16  $OD(16; 1, 1, 2, 2, 2, 2, 2, 2, 2, 2)$  in 9 variables.

The Radon number  $\rho(n)$  gives the maximum number of variables allowed in an orthogonal design of order  $n$  ([10]). Since we have  $\rho(32) = 10$ , we conclude that the

particular orthogonal design of order 32 that we found, has the maximum permissible number of variables.

The algebraic framework that we present here, based on the Cayley-Dickson process, is a systematic way of constructing Orthogonal Designs of order  $2^n$ . A usual, starting from an Orthogonal Design with many variables one can obtain many other Orthogonal Designs by the Equating and Killing variables technique. The full orthogonal design  $\text{OD}(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)$  is just one of the Orthogonal Designs that can be constructed via particular solutions of the equations. To illustrate this point further, we give two full orthogonal designs of order 64 (note that  $\rho(64) = 12$ )

- $\text{OD}(64; 1, 3, 4, 8, 8, 8, 8, 8, 8, 8)$ , with 10 variables
- $\text{OD}(64; 1, 1, 2, 4, 8, 8, 8, 8, 8, 8, 8)$  with 11 variables

in the web page <http://www.cargo.wlu.ca/OD32ineq>. These two full orthogonal designs of order 64 been found by applying the Cayley-Dickson process and finding particular solutions of the systems of polynomial equations that arise after the Gröbner bases calculations.

We note here that the orthogonal design  $\text{OD}(64; 1, 3, 4, 8, 8, 8, 8, 8, 8, 8)$  can be constructed from the orthogonal design  $\text{OD}(64; 1, 1, 2, 4, 8, 8, 8, 8, 8, 8, 8)$  by Equating variables.

### 3 Hadamard matrices from the 10-variable full orthogonal design $\text{OD}(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)$

In this section we use the  $\text{OD}(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)$ , that we denote by  $H_{32}$ , to produce structured Hadamard matrices of orders  $32n$ , where  $n$  is the order of the block matrices  $A, B, C, D, E, F, G, H, I, J$ . Imitating the classical Williamson construction, we take the ten matrices  $A, B, C, D, E, F, G, H, I, J$  to be symmetric circulant matrices of order  $n$  each, defined via the matrix  $U$ :

$$U = \begin{pmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ 1 & 0 & 0 & \dots & 0 \end{pmatrix}.$$

which has the property  $U^n = I_n$ . Take the ten matrices  $A, B, C, D, E, F, G, H, I, J$  to be polynomials in  $U$ , so that they commute with each other:

$$\begin{aligned}
 A &= a_0 I_n + a_1 U + \cdots + a_{n-1} U^{n-1} \\
 B &= b_0 I_n + b_1 U + \cdots + b_{n-1} U^{n-1} \\
 C &= c_0 I_n + c_1 U + \cdots + c_{n-1} U^{n-1} \\
 D &= d_0 I_n + d_1 U + \cdots + d_{n-1} U^{n-1} \\
 E &= e_0 I_n + e_1 U + \cdots + e_{n-1} U^{n-1} \\
 F &= f_0 I_n + f_1 U + \cdots + f_{n-1} U^{n-1} \\
 G &= g_0 I_n + g_1 U + \cdots + g_{n-1} U^{n-1} \\
 H &= h_0 I_n + h_1 U + \cdots + h_{n-1} U^{n-1} \\
 I &= i_0 I_n + i_1 U + \cdots + i_{n-1} U^{n-1} \\
 J &= j_0 I_n + j_1 U + \cdots + j_{n-1} U^{n-1}
 \end{aligned}$$

Since  $U^T = U^{-1}$ , the ten matrices  $A, B, C, D, E, F, G, H, I, J$  will be symmetric if

$$\begin{aligned}
 a_{n-k} &= a_k, b_{n-k} = b_k, c_{n-k} = c_k, d_{n-k} = d_k, e_{n-k} = e_k, \\
 f_{n-k} &= f_k, g_{n-k} = g_k, h_{n-k} = h_k, i_{n-k} = i_k, j_{n-k} = j_k.
 \end{aligned}$$

for  $k = 1, \dots, n - 1$ .

When  $n$  takes specific values, the requirement

$$H_{32} H_{32}^t = (A^2 + 4B^2 + 4C^2 + 4D^2 + 4E^2 + 4F^2 + 4G^2 + 4H^2 + 2I^2 + J^2) \otimes I_{32}$$

(where  $\otimes$  denotes the Kronecker product) can be translated into polynomial equations. Using these polynomial equations we conducted exhaustive and partial searches for the first four odd values of the parameter  $n$ .

Moreover, we need to take into account the diophantine equation

$$a^2 + 4b^2 + 4c^2 + 4d^2 + 4e^2 + 4f^2 + 4g^2 + 4h^2 + 2i^2 + j^2 = 32n \tag{5}$$

where  $a, b, c, d, e, f, g, h, i, j$  are the sums of the elements of the first rows of the matrices  $A, B, C, D, E, F, G, H, I, J$  respectively.

We computed all solutions of equation (5) in positive integers, for  $n = 3, 5, 7, 9$ . For  $n = 3$ , there are 46 solutions. For  $n = 5$ , there are 344 solutions. For  $n = 7$ , there are 1360 solutions. For  $n = 9$ , there are 3731 solutions.

Each solution of equation (5) furnishes additional linear constraints that can be added into the system of polynomial equations we will derive below and thus restrict the search space dramatically.

### 3.1 Exhaustive searches for $n = 3, 5, 7$ and partial search for $n = 9$

In this subsection we report the results of our exhaustive searches for  $n = 3, 5, 7$  and our partial search for  $n = 9$ .

- For  $n = 3$  we obtain the one equation

$$a_0 \cdot a_1 + 4 \cdot b_0 \cdot b_1 + 4 \cdot c_0 \cdot c_1 + 4 \cdot d_0 \cdot d_1 + 4 \cdot e_0 \cdot e_1 + 4 \cdot f_0 \cdot f_1 \\ + 4 \cdot g_0 \cdot g_1 + 4 \cdot h_0 \cdot h_1 + 2 \cdot i_0 \cdot i_1 + j_0 \cdot j_1 + 16 = 0$$

This equation has exactly 28,672 solutions when all 20 variables take  $\pm 1$  values. These solutions give rise to Hadamard matrices of order 96;

- For  $n = 5$  we obtain the two equations

$$a_0 \cdot a_1 + a_1 \cdot a_2 + 4 \cdot b_0 \cdot b_1 + 4 \cdot b_1 \cdot b_2 + 4 \cdot c_0 \cdot c_1 + 4 \cdot c_1 \cdot c_2 \\ + 4 \cdot d_0 \cdot d_1 + 4 \cdot d_1 \cdot d_2 + 4 \cdot e_0 \cdot e_1 + 4 \cdot e_1 \cdot e_2 + 4 \cdot f_0 \cdot f_1 + 4 \cdot f_1 \cdot f_2 \\ + 4 \cdot g_0 \cdot g_1 + 4 \cdot g_1 \cdot g_2 + 4 \cdot h_0 \cdot h_1 + 4 \cdot h_1 \cdot h_2 + 2 \cdot i_0 \cdot i_1 + 2 \cdot i_1 \cdot i_2 \\ + j_0 \cdot j_1 + j_1 \cdot j_2 + 16 = 0$$

$$a_0 \cdot a_2 + a_1 \cdot a_2 + 4 \cdot b_0 \cdot b_2 + 4 \cdot b_1 \cdot b_2 + 4 \cdot c_0 \cdot c_2 + 4 \cdot c_1 \cdot c_2 \\ + 4 \cdot d_0 \cdot d_2 + 4 \cdot d_1 \cdot d_2 + 4 \cdot e_0 \cdot e_2 + 4 \cdot e_1 \cdot e_2 + 4 \cdot f_0 \cdot f_2 \\ + 4 \cdot f_1 \cdot f_2 + 4 \cdot g_0 \cdot g_2 + 4 \cdot g_1 \cdot g_2 + 4 \cdot h_0 \cdot h_2 + 4 \cdot h_1 \cdot h_2 \\ + 2 \cdot i_0 \cdot i_2 + 2 \cdot i_1 \cdot i_2 + j_0 \cdot j_2 + j_1 \cdot j_2 + 16 = 0$$

These two equations have exactly 1,576,960 solutions when all 30 variables take  $\pm 1$  values. These solutions give rise to Hadamard matrices of order 160;

- For  $n = 7$  we obtain the three equations in 40 variables. These three equations have exactly 45,158,400 solutions when all 40 variables take  $\pm 1$  values. These solutions give rise to Hadamard matrices of order 224.
- For  $n = 9$  we obtain four equations in 50 variables. We computed more than 51 million solutions of the system, with a serial C program. These solutions give rise to Hadamard matrices of order 288.

We omit the equations for  $n = 7, 9$ , as and their structure can be easily deduced from the corresponding equations for  $n = 3, 5$ .

#### 4 Inequivalent Hadamard matrices from the full orthogonal design OD(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)

In this section we summarize the computational results on locating inequivalent Hadamard matrices within the sets of Hadamard matrices computed in the previous section. We analyzed the corresponding solution sets with Magma V2.11 to search for inequivalent Hadamard matrices. We used the profile criterion to distinguish between inequivalent Hadamard matrices. The profile criterion is a sufficient (but not necessary) condition for Hadamard inequivalence. Hadamard matrices with unequal profiles are inequivalent. However, Hadamard matrices with equal profiles may or may not be inequivalent. For  $n = 3$ , we located inequivalent matrices of order  $32 \cdot 3 = 96$ . For  $n = 5$ , we located inequivalent matrices of order  $32 \cdot 5 = 160$ . For

$n = 7$ , we located inequivalent matrices of order  $32 \cdot 7 = 224$ . For  $n = 9$ , we located inequivalent matrices of order  $32 \cdot 9 = 288$ .

The doubling method of [9] can be used to produce vast numbers of inequivalent Hadamard matrices of all orders  $8t$ . Nevertheless, it is important to have at our disposal inequivalent Hadamard matrices that don't come from doubling, for coding theory investigations. More specifically, inequivalent Hadamard matrices constructed by the doubling method are not too useful in constructing extremal self-dual codes, see [1]. For this reason, although the lower bounds on the numbers of inequivalent matrices for orders greater than 28 are astronomical, inequivalent Hadamard matrices which are not constructed by a doubling method are greatly needed. Similar facts are of importance in some statistical applications, where inequivalent Hadamard matrices and orthogonal arrays are used as screening designs in some experiments and the related classification problems are of considerable interest, see [12].

The theoretical results of Lam, Lam and Tonchev [15, 16] imply that the number of inequivalent Hadamard matrices of order 96 is greater than or equal to  $10^{49}$  and that the number of inequivalent Hadamard matrices of order 160 is greater than or equal to  $10^{105}$ . Even though these lower bounds are astronomical, the actual numbers of available inequivalent Hadamard matrices (needed for applications) for those orders, are quite small. These theoretical results contain the most powerful lower bounds on Hadamard designs and matrices known presently.

Our computations using the full orthogonal design  $OD(32; 1, 1, 2, 4, 4, 4, 4, 4, 4, 4)$  yield many inequivalent Hadamard matrices of orders 96, 160, 224, 288. The results are summarized in the web page <http://www.cargo.wlu.ca/OD32ineq>

## 5 Discussion and Future Research

The method presented in this paper is more general than the doubling method, because it can produce some orthogonal designs that cannot be constructed by doubling. Such an example is the orthogonal design  $OD(16; 1, 1, 7, 7)$  presented in [14] (see overleaf).

The orthogonal design  $OD(16; 1, 1, 7, 7)$  cannot be obtained from the orthogonal design  $OD(16; 1, 1, 2, 2, 2, 2, 2, 2)$ , or by doubling of an orthogonal design of order 8. The orthogonal design  $OD(16; 1, 1, 7, 7)$  can be constructed from simple Paley matrices.

The orthogonal design  $OD(128; 8_{16})$  is given as conjecture 2.117 (page 295) in the second edition of the Handbook of Combinatorial Designs [7]. We believe that it is possible to construct  $OD(128; 8_{16})$  with the method presented in this paper.



A	H	H	H	H	H	H	H	I	J	J	J	J	J	J	J
-H	A	-H	H	-H	H	H	-H	-J	I	J	-J	J	-J	-J	J
-H	H	A	-H	-H	-H	H	H	-J	-J	I	J	J	J	-J	-J
-H	-H	H	A	-H	H	-H	H	-J	J	-J	I	J	-J	J	-J
-H	H	H	H	A	-H	-H	-H	-J	-J	-J	-J	I	J	J	J
-H	-H	H	-H	H	A	H	-H	-J	J	-J	J	-J	I	-J	J
-H	-H	-H	H	H	-H	A	H	-J	J	J	-J	-J	J	I	-J
-H	H	-H	-H	H	H	-H	A	-J	-J	J	J	-J	-J	J	I
-I	J	J	J	J	J	J	J	A	-H	-H	-H	-H	-H	-H	-H
-J	-I	J	-J	J	-J	-J	J	H	A	H	-H	H	-H	-H	H
-J	-J	-I	J	J	J	-J	-J	H	-H	A	H	H	H	-H	-H
-J	J	-J	-I	J	-J	J	-J	H	H	-H	A	H	-H	H	-H
-J	-J	-J	-J	-I	J	J	J	H	-H	-H	-H	A	H	H	H
-J	J	-J	J	-J	-I	-J	J	H	H	-H	H	-H	A	-H	H
-J	J	J	-J	-J	J	-I	-J	H	H	H	-H	-H	H	A	-H
-J	-J	J	J	-J	-J	J	-I	H	-H	H	H	-H	-H	H	A

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