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RESEARCH MEMORANDUM

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A DESIGN AND A CODE INVARIANT UNDER THE SIMPLE GROUP Co_3

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FEW 458

A DESIGN AND A CODE INVARIANT UNDER THE SIMPLE GROUP Co_3

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In memory of Professor Marshall Hall

ABSTRACT

A self-orthogonal doubly-even (276,23) code invariant under the Conway simple group Co_3 is constructed. The minimum weight codewords form a $2\text{-}(276,100,2\cdot 3^6)$ doubly-transitive block-primitive design with block stabilizer isomorphic to the Higman-Sims simple group HS. More generally, the codewords of any given weight are single orbits stabilized by maximal subgroups of Co_3. The restriction of the code on the complement of a minimum weight codeword is the (176,22) code discovered by Calderbank and Wales as a code invariant under HS.

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*) Part of this work was done while these two authors were at the University of Giessen, W. Germany, the first as a NATO Research Fellow, and the second as a Research Fellow of the Alexander von Humboldt Foundation.

1. The design

We assume that the reader is familiar with the basic notions and elementary facts from design and coding theory. Our notation follows that from [1], [3], [7], [12], [13], [15] and for groups [5]. We also use some ideas from the theory of strongly regular graphs and regular two-graphs [3], [6], [14].

The design we are going to discuss can be constructed in the spirit of the work by Marshall Hall, Lane and Wales [8], namely by using orbits under finite permutation groups.

The Conway simple group Co_3 can be characterized as the full automorphism group acting 2-transitively on a unique two-graph Ω on 276 vertices [4], [6], [14]. The Higman-Sims simple group HS [9] is a maximal subgroup of Co_3 splitting the vertices of Ω into two orbits of length 100 and 176 respectively, and acting 2-transitively on the orbit of length 176 and as a rank 3 group on the orbit of length 100. The orbit of the set of 100 vertices of G fixed by HS under Co_3 is a 2-design D with 11178 blocks, i.e. a 2-$(276,100,2\cdot 3^6)$ design on which Co_3 acts doubly-transitively on points and primitively on blocks.

An explicit construction of the design D is obtained by the following permutation presentation of Co_3 which was found by computer using the group theory language CAYLEY. The following two permutations generate Co_3 acting 2-transitively on 276 points:

α = (2 24 3)(4 5 7)(8 189 150)(9 184 144)(10 190 149)(11 183 143)
(12 192 156)(13 191 153)(14 181 154)(15 182 155)(16 196 146)
(17 194 148)(18 195 147)(19 193 145)(20 188 151)(21 186 152)
(22 185 141)(23 187 142)(25 26 27)(29 49 200)(30 50 199)(31 51 198)
(32 52 197)(33 57 226)(34 58 225)(35 59 228)(36 60 227)(37 55 204)
(38 56 203)(39 53 202)(40 54 201)(41 47 206)(42 48 205)(43 45 208)
(44 46 207)(61 121 172)(62 122 171)(63 123 169)(64 124 170)
(65 127 158)(66 128 157)(67 125 160)(68 126 159)(69 138 162)
(70 137 161)(71 139 164)(72 140 163)(73 118 174)(74 117 173)
(75 120 176)(76 119 175)(77 131 177)(78 132 178)(79 130 180)
(80 129 179)(81 134 168)(82 133 167)(83 136 166)(84 135 165)

(85 91 97)(86 90 98)(89 100 95)(92 99 96)(101 107 113)(102 108 114)
(103 105 115)(104 106 116)(209 232 266)(210 236 268)(211 239 272)
(212 233 263)(213 231 271)(214 241 265)(215 244 275)(216 237 267)
(217 242 269)(218 235 274)(219 229 264)(220 234 273)(221 240 261)
(222 243 262)(223 230 270)(224 238 276)(245 255 248)(246 258 253)
(247 250 257)251 252 259);

β = (1 117 120 125)(2 78 113 111)(4 167 166 89)(5 148 174 170)
(6 12 56 214)(7 33 250 141)(8 181 25 71)(9 136 124 119)
(10 20 132 178)(11 31 155 213)(13 35 187 264)(14 193 51 210)
(15 240 191 216)(16 152 59 212)(17 137 60 29)(18 134 46 55)
(19 231 233 61)(21 130 58 232)(22 199 189 222)(23 118 197 201)
(24 86 92 159)(26 112 70 267)(27 263 235 194)(28 198 62 228)
(30 224 266 218)(32 140 50 154)(34 40 47 248)(36 244 225 239)
(37 153)(38 176 249 87)(39 165 158 252)(41 150 145 234)
(42 256 162 99)(43 49 52 220)(44 259 192 67)(45 114 79 82)
(48 175 149 247)(53 223 202 207)(54 205 126 122)(57 188 274 138)
(63 80 275 237)(64 72 206 219)(65 236)(66 186 106 268)
(68 271 257 177)(69 273 171 217)(73 164 246 229)(74 102 103 93)
(76 183 258 243)(77 226 196 242)(81 251 168 115)(83 109)
(84 157 173 97)(88 238)(90 262 245 180)(91 95 104 108)
(94 253 116 98)(96 161 107 269)(110 270 215 241)(121 143 146 142)
(128 221)(131 190 139 151)(133 211)(135 200)(147 179 265 261)
(163 260)(169 276 272 185)(172 254)(182 184 208 227)(195 255).

As a base block of our design D we can take the first 100 points 1,2,...,100 since the set-wise stabilizer of this 100-subset turns out to be precisely a group isomorphic to HS.

Since Co_3 has rank 5 presentation on the blocks of D, there are at most four (in fact precisely four) intersection numbers: 34, 36, 44, 50. The numbers n_i (i = 34, 36, 44, 50) of blocks intersecting a given block in precisely i points are listed in Table 1.

Let X denote the set of 276 points of D and let B be a block of D. Since the stabiliser of B, a HS, acts 2-transitively on X\B, the blocks intersecting B in a constant number i of points form a 2-design on X\B

i	n_i
34	5600
36	4125
44	1100
50	352

Table 1. Block intersection numbers of D

with 176 points and n_i blocks. The values of n_i for i = 34, 36, 44 from Table 1 correspond to indices of maximal subgroups of HS (cf. [5]). Therefore, the designs obtained in this way are block primitive under HS. In the case i=50 the 352 blocks intersecting B in 50 points split into two classes of 176 blocks each in such a way that if B_1 and B_2 intersect B in 50 points and are disjoint on B then B_1 and B_2 coincide on X\B. Therefore, the restrictions of the blocks intersecting B in 50 points on X\B form the well-known symmetric 2-(176,50,14) design discoverd first by G. Higman [10].

2. The code

Since the block size is $100 \equiv 0 \pmod 4$ and all block intersection numbers are even (i.e., the design D is self-orthogonal in the terminology of [16]), the rows of the block-point incidence matrix of D generate a self-othogonal binary code C_{276} of length 276 with all weights divisible by 4, i.e. C_{276} is a doubly-even code. Consequently, the dimension of C_{276} is at most 276/2 = 138. However, the actual dimension turns out to be as small as 23. A generator matrix for the code is obtained by taking the images of the vector of length 276 and weight 100 with the first 100 positions equal to 1 under the cyclic group of order 23 generated by the following element y of Co_3:

y = (1 191 184 195 28 63 50 245 5 100 11 97 33 135 218 58 84 76 43 181 130 151 231)(2 196 246 222 40 36 203 41 83 68 177 260 47 129 263 34 77 228 85 10 79 150 13)(3 22 271 70 143 145 19 193 138 82 257 221 148 20 4 9 241 103 205 105 242 157 37)(6 175 171 206 252 87 266 140 39 88 155 119 229 185 66 94 136 227 247 152 115 256 7)(8 51 240 108 134 170 192 81 158 189 52 176 141 264 249 212 200 235 166 29 111 96 12)(14 60 210 262 179 118 174 30 42 75 232 54 99 64 202 214 217 46 122 215 188 194 234) (15 244 107 38 71 104 123 163 137 258 144 219 182 153 49 265 261 259 16 272 55 156 35) (17 243 173 61 268 147 48 238 159 124 91 213 236 113 102 109 169 274 216 207 201 31 237)(18 95 160 65 270 230 116 142 44 225 255 226 56 110 89 233 167 23 276 199 187 198 132)(21 121 93 57 25 275 172 220 139 114 209 73 223 248 90 128 146 204 178 133 208 127 74) (24 101 269 53 98 251 186 273 164 92 27 80 131 62 67 86 72 211 190 168 125 45 161)(26 162 197 149 254 32 78 180 165 117 267 112 239 183 224 106 59 126 120 250 154 69 253).

The weight distribution of this code was computed by Jesse Nemoyer and is listed in Table 2.

i	$A_i = A_{276-i}$
0	1
100	11178
112	37950
128	1536975
132	2608200

Table 2. The weight distribution of the code C_{276}.

Notes

(i) It is remarkable that the possible weights are determined by the block intersection numbers (cf. Table 1) and the all-one vector. Furthermore, the minimum weight codewords are precisely the blocks of the design D.

(ii) By the 2-transitivity of Co3 on the code coordinates, the codewords of any fixed weight w form a 2-design. As seen from the list of maximal groups of Co3 [5], the stabilizer of any (non-zero) codeword is a maximal subgroup of Co3:

$w = 100$: HS;
$w = 112$: $U_4(3):(2^2)_{133}$;
$w = 128$: $2^4.A_8$;
$w = 132$: $2 \times M_{12}$.

Therefore, for all designs the group Co3 acts primitively on blocks.

(iii) Removing a codeword x of minimum weight and deleting the 100 code coordinates corresponding to the support of x leads to a (176,22) code C_{176} invariant under the Higman-Sims simple group with weight distribution listed in Table 3. In fact this is precisely the code discovered by Calderbank and Wales [2]. This gives a natural embedding of the Higman-Sims group into the Conway group Co3.

i	$A_i = A_{176-i}$
0	1
50	176
56	1100
64	4125
66	5600
70	17600
72	15400
78	193600
80	604450
82	462000
86	369600
88	847000

Table 3. The weight distribution of the code C

The stabilizers of codewords of weight 50, 56, 64, 66 and 72 are maximal subgroups of HS. The codewords in C_{176} of the first four non-zero weights are precisely the restrictions of the blocks of D distinct from x on the complement of x (cf. Table 1).

3. A construction from the McLaughlin graph

In this section we give a computer-free argument for the dimension of the row space of the incidence matrix of the design D, i.e. the dimension of the code C_{276}, as well as a construction of D and C_{276} based on the McLaughlin simple group [11] and the related rank 3 graph on 275 vertices and regular two-graph on 276 vertices [4], [6], [14].

Theorem. Let A be the (0,1)-adjacency matrix of the McLaughlin strongly regular graph with parameters (in the notation of [3]) $n=275$, $a=112$, $c=30$, $d=56$, and eigenvalues $r=2$, $s=-28$. Then the binary code C generated by the columns of the following matrix G,

$$G = \begin{bmatrix} 1 & 0 \ \ldots \ 0 \\ \vdots & \\ & A \\ 1 & \end{bmatrix}$$

has dimension 23 and is equivalent to C_{276}.

Proof. Since all columns of G have even weights and the scalar product of any pair of columns is even, the column space of G is a binary self-orthogonal code of length 276. In view of the preceding observatons, it is enough to show that the dimension of this column space is at most 23, and the blocks of D are among the codewords of weight 100.

Put $E = A-10I-2J$ (I is the identity and J the all-one matrix). Then rank $E = 22$ (the multiplicity of -28 in A). Hence $\operatorname{rank}_2 E \le 22$, so $\operatorname{rank}_2 A \le 22$ and $\dim C \le 23$.

Let McL denote the McLauglin graph on 275 vertices. The graph McL extended by an isolated vertex ∞ is in the switching class of the regular two-graph Ω on 276 vertices for which Co_3 is the full automorphism group. Then Ω can be represented by the following graph in its switching class:

$$A^* = \begin{array}{c} \begin{bmatrix} 0 & N_0 \\ & \\ N_0^T & B_0 \end{bmatrix} \\ \begin{array}{cc} \overset{\longleftrightarrow}{23} & \overset{\longleftrightarrow}{253} \end{array} \end{array} = \begin{array}{c} \begin{bmatrix} 0 & \ldots\; 0 & 1 \;\ldots\; 1 & 0 \;\ldots\; 0 \\ \vdots & 0 & N_1 & N_2 \\ 0 & & & \\ 1 & & & \\ \vdots & N_1^T & B_1 & B_{12} \\ 1 & & & \\ 0 & & & \\ \vdots & N_2^T & B_{12}^T & B_2 \\ 0 & & & \end{bmatrix} \\ \begin{array}{ccc} & \overset{\longleftrightarrow}{77} & \overset{\longleftrightarrow}{176} \end{array} \end{array},$$

where: N_0 is an incidence matrix of the unique quasi-symmetric 4-(23,7,1) design; N_1 is its derived and N_2 its residual design; and B_1 $(i = 0,1,2)$ is the adjacency matrix of the block graph of N_i. The group $HS < Co_3$ has an orbit O_1 of size 100 and an orbit O_2 of size 176 on Ω. The sub two-graph induced by O_2 is the Higman-Sims regular two-graph Ω'. In the representation above Ω' is represented by B_2, and O_1 induces

$$C = \begin{bmatrix} 0 & \ldots\; 0 & 1 \;\ldots\; 1 \\ \vdots & 0 & N_1 \\ 0 & & \\ 1 & & \\ \vdots & N_1^T & B_1 \\ 1 & & \end{bmatrix}.$$

Note that if we switch with respect to the upper left entry, C becomes the adjacency matrix of the Higman-Sims strongly regular graph on 100 vertices with valency 22.

If ∞ does not belong to O_2, we can choose to isolate, by switching, the upper left entry of A^* in order to obtain A. Then

$$A = \begin{bmatrix} 0 & J-N_1 & N_2 \\ J-N_1^T & B_1 & J-B_{12} \\ N_2^T & J-B_{12}^T & B_2 \end{bmatrix}.$$

The row sum matrix is then

$$\begin{bmatrix} 0 & 56 & 56 \\ 16 & 16 & 80 \\ 7 & 35 & 70 \end{bmatrix}.$$

Thus the 77 columns in the middle add up to O_2.

If $\infty \in O_2$, then isolate, by switching, a vertex of B_2. The remaining vertices of O_2 represent a strongly regular graph H with 175 vertices and valency 72. After the switching O_1 induces a switched Higman-Sims graph, and thus we have the following structure for A.

$$A = \begin{bmatrix} B_3 & B_{34} & N_3 \\ B_{34}^T & B_4 & N_4 \\ N_3^T & N_4^T & B_2^* \end{bmatrix}, \\ \begin{array}{ccc} \longleftrightarrow & \longleftrightarrow & \longleftrightarrow \\ 50 & 50 & 175 \end{array}$$

where B_2^* is the adjacency matrix of H, the matrix

$$\begin{bmatrix} B_3 & J-B_{34} \\ J-B_{34}^T & B_4 \end{bmatrix}$$

represents the Higman-Sims graph and B_3 and B_4 are regular with valency 7 (in fact, B_3 and B_4 are Hoffman-Singleton graphs). The row sum matrix now is

$$\begin{bmatrix} 7 & 35 & 70 \\ 35 & 7 & 70 \\ 20 & 20 & 72 \end{bmatrix}.$$

Hence, the first 51 columns of C add up to 0_2.

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