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## Orthogonal Designs from Negacyclic Matrices

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# Orthogonal Designs from Negacyclic Matrices

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## Abstract

We study the use of negacyclic matrices to form orthogonal designs and hence Hadamard matrices. We give results for all possible tuple for order 12, all but 3 for order 20 and all but 3 for order 28.

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AMS Subject Classification:

## 1 Introduction

An *orthogonal design* of order  $n$  and type  $(s_1, s_2, \dots, s_k)$  in variables  $x_1, x_2, \dots, x_k$ , denoted  $OD(n; s_1, s_2, \dots, s_k)$ , is a matrix  $A$  of order  $n$  with entries in the set  $\{0, \pm x_1, \pm x_2, \dots, \pm x_k\}$  satisfying

$$AA^T = \left(\sum_{i=1}^k s_i x_i^2\right) I_n,$$

where  $I_n$  is the identity matrix of order  $n$ . Alternatively, the rows of  $A$  are formally orthogonal and each row has precisely  $s_i$  entries of the type  $\pm x_i$ . In [1], where this was first defined, it was mentioned that

$$A^T A = \left(\sum_{i=1}^k s_i x_i^2\right) I_n$$

and so our alternative description of  $A$  applies equally well to the columns of  $A$ .

An *Hadamard matrix*  $H$  of order  $n$  is a square  $(1, -1)$  matrix having inner product of distinct rows zero. Hence  $HH^T = nI_n$ . We note that  $n = 1, 2$  or  $n \equiv 0 \pmod{4}$ .

A matrix  $A \pm I$  is *skew-type* if  $A$  has zero diagonal and  $A^T = -A$ . A skew-type Hadamard matrix is said to be *skew-Hadamard*.

*Circulant matrices* of order  $n$  are polynomials in the shift matrix

$$S = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & & 0 \\ \vdots & & & & \vdots \\ 0 & 0 & 0 & & 1 \\ 1 & 0 & 0 & & 0 \end{pmatrix}.$$

*Negacyclic matrices* of order  $n$  are polynomials in the negashift matrix

$$N = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & & 0 \\ \vdots & & & & \vdots \\ 0 & 0 & 0 & & 1 \\ -1 & 0 & 0 & & 0 \end{pmatrix}.$$

The *back-diagonal matrix*  $R$  of order  $n$  is the matrix whose elements  $r_{ij}$  are given by

$$r_{ij} = \begin{cases} 1 & \text{if } i + j = n + 1, \\ 0 & \text{otherwise} \end{cases}$$

where  $i, j = 1, \dots, n$ . We note that if  $A, B$  are polynomial in  $S$  then  $A(BR)^T = (BR)A^T$ . We show below that the same is true if  $A, B$  are polynomial in  $N$ .

Lastly, we define the *nonperiodic autocorrelation function*. Let

$$X = \{\{a_{11}, \dots, a_{1n}\}, \{a_{21}, \dots, a_{2n}\}, \dots, \{a_{m1}, \dots, a_{mn}\}\}$$

be  $m$  sequences of commuting variables of length  $n$ . Then the nonperiodic autocorrelation function of the family of sequences  $X$  (denoted  $N_X$ ) is the function defined by

$$N_X(j) = \sum_{i=1}^{n-j} (a_{1,i}a_{1,i+j} + a_{2,i}a_{2,i+j} + \cdots + a_{m,i}a_{m,i+j}).$$

## 2 Preliminary results

We note some properties of the negashift matrix  $N$  given above:

$$(N^i)^T = -N^{n-i} \quad \text{and} \quad N^i R = -R N^{n-i}.$$

Hence we have:

**Lemma 1**  $N^i(N^j R)^T = (N^j R)(N^i)^T$ .

**Proof.**  $N^i(N^j R)^T = N^i R (N^j)^T = -N^i R N^{n-j} = N^i N^j R = N^j N^i R = -N^j R N^{n-i} = (N^j R)(N^i)^T$ .  $\square$

**Lemma 2** Suppose  $A, B$  are polynomial in  $S$  or  $N$  then  $A(BR)^T = (BR)A^T$ .

**Proof.** The result for  $S$ , circulant, can be found in Wallis [6]. For  $N$ , negacyclic, we note  $A$  and  $B$  are polynomials in  $N$  so by repeated applications of Lemma 1 we have the result.  $\square$

We now develop some properties of negacyclic matrices.

**Theorem 1** Let  $R_i, R_j$  be two rows of a negacyclic matrix of dimension  $n$ , where  $1 < i < j \leq n$ . Then  $R_i R_j^T = R_1 R_{1+j-i}^T$ .

**Proof.** Let  $i = 1 + s$  and  $j = 1 + s + t$ . If we write  $R_1 = (x_1, \dots, x_n)$ , we have

$$\begin{aligned} R_{1+s} &= (-x_{n-s+1}, \dots, -x_n, x_1, \dots, x_{n-s}) \\ R_{1+t} &= (-x_{n-t+1}, \dots, -x_n, x_1, \dots, x_{n-t}) \\ R_{1+s+t} &= (-x_{n-s-t+1}, \dots, -x_n, x_1, \dots, x_{n-s-t}) \end{aligned}$$

We note that

$$\begin{aligned} R_{1+s} &= (\overbrace{-x_{n-s}, \dots, -x_n}^s, \overbrace{x_1, \dots, x_t}^t, x_{t+1}, \dots, x_{n-s}) \\ R_{1+s+t} &= (\underbrace{-x_{n-s-t+1}, \dots, -x_{n-t}}_s, \underbrace{-x_{n-t+1}, \dots, -x_n}_t, x_1, \dots, x_{n-s-t}) \end{aligned}$$

Then

$$\begin{aligned} R_i R_j^T &= R_{1+s} R_{1+s+t}^T \\ &= x_{n-s+1} x_{n-s-t+1} + \dots + x_n x_{n-t} - x_1 x_{n-t+1} - \dots - x_t x_n \\ &\quad + x_{t+1} x_1 + \dots + x_{n-s} x_{n-s-t} \\ &= -x_1 x_{n-t+1} - \dots - x_t x_n + x_{t+1} x_1 + \dots + x_{n-s} x_{n-s-t} \\ &\quad + x_{n-s+1} x_{n-s-t+1} + \dots + x_n x_{n-t} \\ &= -x_1 x_{n-t+1} - \dots - x_t x_n + x_{t+1} x_1 + \dots + x_n x_{n-t} \\ &= R_1 R_{1+t}^T \\ &= R_1 R_{1+j-i}^T \end{aligned}$$

□

**Corollary 1** *For a negacyclic matrix of odd dimension  $n$ , there are only  $n$  inner products of interest, i.e. each row with the first. More precisely, for a negacyclic matrix of odd dimension  $n$ , there are  $\frac{n+1}{2}$  distinct inner products,  $p_1, p_2, p_3, \dots, p_{\frac{n+1}{2}}$ , where  $p_i = R_1 R_i^T$ . The remaining  $\frac{n-1}{2}$  inner products are related by the property that  $-p_{\frac{n+1}{2}+q} = p_{\frac{n+3}{2}-q}$ , for  $1 \leq q \leq \frac{n-1}{2}$ .*

**Corollary 2** *For a negacyclic matrix of odd dimension  $n$ ,  $R_1 R_i^T = -R_1 R_{n-i+2}^T$  for  $1 < i \leq n$ .*

**Definition 1** *Let  $L, M$  be two negacyclic matrices of dimension  $n$ . We say  $L$  and  $M$  are in the same inner product equivalence class if for every  $1 \leq i, j \leq n$ ,  $R_i R_j^T$  of  $L$  equals  $R_i R_j^T$  of  $M$ .*

**Theorem 2** *Let  $M$  be a negacyclic matrix of dimension  $n$ , with first row*

$$m_1, m_2, \dots, m_n.$$

*Then the negacyclic matrices with first rows*

$$-m_1, -m_2, \dots, -m_n \quad \text{and} \quad m_n, m_{n-1}, \dots, m_1$$

*(denoted  $-M$  and  $M^*$  respectively) are in the same inner product equivalence class as  $M$ .*

**Proof.** By Theorem 1, we need only consider the inner products of rows  $R_1$ ,  $R_{1+j}$  for  $1 \leq j \leq n-1$ . We observe that for the matrix  $M$ ,

$$\begin{aligned} R_1 &= m_1 & m_2 & \cdots & m_j & m_{j+1} & m_{j+2} & \cdots & m_n \\ R_{1+j} &= -m_{n-j+1} & -m_{n-j+2} & \cdots & -m_n & m_1 & m_2 & \cdots & m_{n-j}. \end{aligned}$$

Likewise, for the matrix  $-M$ ,

$$\begin{aligned} R_1 &= -m_1 & -m_2 & \cdots & -m_j & -m_{j+1} & -m_{j+2} & \cdots & -m_n \\ R_{1+j} &= m_{n-j+1} & m_{n-j+2} & \cdots & m_n & -m_1 & -m_2 & \cdots & -m_{n-j}. \end{aligned}$$

Similarly, for the matrix  $M^*$ ,

$$\begin{aligned} R_1 &= m_n & m_{n-1} & \cdots & m_{n-j+1} & m_{n-j} & m_{n-j-1} & \cdots & m_1 \\ R_{1+j} &= -m_j & -m_{j-1} & \cdots & -m_1 & m_n & m_{n-1} & \cdots & m_{j+1}. \end{aligned}$$

The inner product of  $R_1$  with  $R_{1+j}$  is the same in all three cases, namely

$$\begin{aligned} R_1 R_{1+j}^T &= -m_1 m_{n-j+1} - m_2 m_{n-j+2} - \cdots - m_j m_n \\ &\quad + m_1 m_{j+1} + m_2 m_{j+2} + \cdots + m_{n-j} m_n \\ &= -\sum_{i=1}^j m_i m_{n-j+i} + \sum_{i=1}^{n-j} m_i m_{i+j}. \end{aligned}$$

Hence  $M$ ,  $-M$  and  $M^*$  are in the same inner product equivalence class.  $\square$

**Corollary 3** *Given a negacyclic matrix  $M$ , the negacyclic matrix  $-M^*$  is in the same inner product equivalence class as  $M$ .*

**Theorem 3** *Let  $M$  be a negacyclic matrix with first row  $R_1 = (m_1, \dots, m_n)$ . Then every negacyclic matrix  $M'$  with a first row  $R'_1$  equal to a negashift of  $R_1$  is in the same inner product equivalence class as  $M$ . (There are  $2n-1$  negashifts of  $R_1$ .)*

**Proof.** The  $2n-1$  negashifts of  $R_1$  are

$$R_2, \dots, R_n, -R_1, \dots, -R_n$$

where  $R_i$  is the  $i$ th row of the matrix  $M$ .

By Theorem 2, the negacyclic matrix with first row equal to  $-R_1$  is in the same inner product equivalence class as  $M$ . Likewise, the negacyclic matrices with first rows equal to  $-R_2, \dots, -R_n$  are in the same inner product equivalence class as the negacyclic matrices with first rows  $R_2, \dots, R_n$  respectively. Thus we need consider only the negacyclic matrices with first rows  $R'_1 = R_i$ , where  $2 \leq i \leq n$ .

Let  $M'$  be a negacyclic matrix with first row  $R'_1 = R_i$  for some  $i$  in the range  $2 \leq i \leq n$ . By Corollary 1,  $M'$  has only  $\frac{n+1}{2}$  distinct inner products, namely  $R'_1 (R'_j)^T$ , for  $2 \leq j \leq \frac{n+1}{2}$ .

Now,  $R'_1 = R_i$ , and

$$R'_{\frac{n+1}{2}} = \begin{cases} R_{i+\frac{n-1}{2}} & \text{for } 2 \leq i \leq \frac{n+1}{2} \\ -R_{i+\frac{n-1}{2}-n} & \text{for } \frac{n+3}{2} \leq i \leq n. \end{cases}$$

We consider the two cases in turn.

**Case I:** When  $2 \leq i \leq \frac{n+1}{2}$ , the rows  $R'_1, \dots, R'_{\frac{n+1}{2}}$  are all from  $M$ . Then the inner product  $R'_1(R'_j)^T$  for  $2 \leq j \leq \frac{n+1}{2}$  is:

$$\begin{aligned} R'_1(R'_j)^T &= R_i R_{i+j-1}^T \\ &= R_1 R_j^T \quad (\text{by Theorem 1}). \end{aligned}$$

Thus the negacyclic matrices  $M'$  with first row  $R'_1 = R_i$  for  $2 \leq i \leq \frac{n+1}{2}$  are in the same inner product equivalence class as  $M$ .

**Case II:** When  $\frac{n+3}{2} \leq i \leq n$ , the rows  $R'_1, \dots, R'_{n-i+1}$  are from  $M$ , and the rows  $R'_{n-i+2}, \dots, R'_{\frac{n+1}{2}}$  are from  $-M$ . For  $2 \leq j \leq n-i+1$ ,  $R'_1(R'_j)^T = R_1 R_j^T$  by the argument presented in Case I. For  $n-i+2 \leq j \leq \frac{n+1}{2}$ , we have

$$\begin{aligned} R'_1(R'_j)^T &= R_i R_{i+j-1-n}^T \\ &= -R_1 R_{n-j+2} \quad (\text{observe } i+j-1-n < i \\ &\quad \text{and then apply Theorem 1}) \\ &= R_1 R_j \quad (\text{by Corollary 2}). \end{aligned}$$

Thus the negacyclic matrices  $M'$  with first row  $R'_1 = R_i$  for  $\frac{n+3}{2} \leq i \leq n$  are in the same inner product equivalence class as  $M$ .

Hence the  $2n-1$  negacyclic matrices which have a first row equal to a negashift of the first row of  $M$  are all in the same inner product equivalence class as  $M$ .  $\square$

We note from Wallis and Whiteman [7] that circulant can be replaced by group-type or type 1 in abelian groups so that all results that follow for circulant also follow for group-type or type 1. Similarly we observe that group-type or type 1 negacyclic can be used instead of negacyclic and the corresponding results hold. So we have, modifying Goethals-Seidel construction [6]:

**Theorem 4** *Suppose there exist four negacyclic  $(1, -1)$  matrices  $A, B, C, D$  of order  $n$ . Further, suppose*

$$AA^T + BB^T + CC^T + DD^T = 4nI_n.$$

*Then*

$$SF = \begin{bmatrix} A & BR & CR & DR \\ -BR & A & D^T R & -C^T R \\ -CR & -D^T R & A & B^T R \\ -DR & C^T R & -B^T R & A \end{bmatrix} \quad (1)$$

*is an Hadamard matrix of order  $4n$  of SF type. (Here  $R$  is the back diagonal matrix.) If  $A$  is of skew-type, then  $SF$  is skew-Hadamard.*

### 3 Our results

**Definition 2** *A set of four negacyclic matrices  $A, B, C, D$  is said to be suitable if*

$$AA^T + BB^T + CC^T + DD^T = fI$$

*for some  $f$ .*

**Theorem 5** *If there exist four sequences with zero non-periodic autocorrelation function, then there exist four suitable negacyclic matrices.*

**Proof.** Let there be four sequences of length  $n$ , denoted

$$X = \{\{a_1, a_2, \dots, a_n\}, \{b_1, b_2, \dots, b_n\}, \{c_1, c_2, \dots, c_n\}, \{d_1, d_2, \dots, d_n\}\},$$

with zero non-periodic autocorrelation function. We now treat each of these sequences as the first row of a negacyclic matrix. The matrices generated in this way are denoted  $A, B, C, D$  respectively. We consider the sum

$$AA^T + BB^T + CC^T + DD^T.$$

For a negacyclic matrix  $M$ , the element  $(i, j)$  of the product  $MM^T$  is equal to  $R_i R_j^T$ , where  $R_i, R_j$  are the  $i$ th and  $j$ th rows of  $M$  respectively. By Theorem 1, it is sufficient to consider only the products  $R_1 R_{1+j}^T$ , for  $1 \leq j \leq n-1$ . We recall that

$$R_1 R_{1+j}^T = - \sum_{i=1}^j m_i m_{n-j+i} + \sum_{i=1}^{n-j} m_i m_{i+j}$$

(as shown in the proof of Theorem 2).

Thus the sum of the products  $R_1 R_{1+j}^T$  of  $A, B, C$  and  $D$ , for  $1 \leq j \leq n-1$ , is equal to

$$\begin{aligned} & - \sum_{i=1}^j (a_i a_{n-j+i} + b_i b_{n-j+i} + c_i c_{n-j+i} + d_i d_{n-j+i}) \\ & + \sum_{i=1}^{n-j} (a_i a_{i+j} + b_i b_{i+j} + c_i c_{i+j} + d_i d_{i+j}) \\ = & -N_X(n-j) + N_X(j) \\ = & 0 \end{aligned}$$

By Theorem 1, the off-diagonal element  $(i, j)$ , where  $i \neq j$ , of the sum  $AA^T + BB^T + CC^T + DD^T$ , is equal to element  $(1, 1+j-i)$ . As has just been shown, these elements all equal to 0. Thus all off-diagonal elements of the sum are 0.

Lastly, we consider the diagonal elements. It is clear that element  $(j, j) = \sum_{i=1}^n (a_i^2 + b_i^2 + c_i^2 + d_i^2)$  for  $1 \leq j \leq n$ . Write this sum as  $f$ . Thus we have

$$AA^T + BB^T + CC^T + DD^T = fI$$

and so the negacyclic matrices  $A, B, C, D$  are suitable.  $\square$

**Corollary 4** *The four suitable negacyclic matrices  $A, B, C, D$  that were constructed in the last proof satisfy*

$$AA^T + BB^T + CC^T + DD^T = 4nI_n.$$

*Hence, by Theorem 4, we can produce an Hadamard matrix of order  $4n$  of SF-type.*

We have found that suitable negacyclic matrices are not limited to those generated from sequences with a zero non-periodic autocorrelation function. The appendix contains a listing of negacyclic sequences of order  $n = 3, 5, 7$  which are suitable, and so yield SF-type Hadamard matrices and orthogonal designs of order  $4n$ .



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## A Negacyclic sequences with zero autocorrelation function

### Order 12

Design	A			B			C			D		
(1,1,1,1)	a	0	0	b	0	0	c	0	0	d	0	0
(1,1,1,4)	a	0	0	b	0	0	c	d	d	0	d	-d
(1,1,1,9)	a	d	d	b	d	d	c	d	d	d	-d	d
(1,1,2,2)	a	0	0	b	0	0	c	-d	0	c	d	0
(1,1,2,8)	a	d	d	b	d	d	-c	-d	d	c	-d	d
(1,1,4,4)	a	d	d	b	c	c	0	-c	c	0	-d	d
(1,1,5,5)	a	d	d	b	c	c	d	-c	c	-c	-d	d
(1,2,2,4)	0	d	-d	a	d	d	b	c	0	b	-c	0
(1,2,3,6)	a	d	-d	c	d	d	c	a	-d	c	-a	d
(2,2,2,2)	a	b	0	a	-b	0	c	d	0	c	-d	0
(2,2,4,4)	a	b	b	d	b	-b	c	d	d	-b	d	-d
(3,3,3,3)	a	b	c	b	-c	d	c	d	-a	d	a	-b

### Order 20

Design	A, C					B, D				
(1,1,1,1)	a	0	0	0	0	b	0	0	0	0
	c	0	0	0	0	d	0	0	0	0
(1,1,1,4)	a	0	0	0	0	b	0	0	0	0
	c	0	d	d	0	0	0	d	-d	0
(1,1,1,9)	a	0	d	d	0	b	0	d	d	0
	c	d	0	0	d	d	-d	d	0	0
(1,1,2,2)	a	0	0	0	0	b	0	0	0	0
	c	-d	0	0	0	d	c	0	0	0

(1,1,2,8)	a 0 d d 0	b 0 d d 0
	c 0 d -d 0	-c 0 d -d 0
(1,1,4,4)	a 0 c c 0	0 0 c -c 0
	b 0 d d 0	0 0 d -d 0
(1,1,4,9)	a 0 d d 0	b 0 d d 0
	0 -d c -c -d	d -d c c d
(1,1,5,5)	a 0 c c 0	b 0 d d 0
	c 0 d -d 0	-d 0 c -c 0
(1,1,8,8)	a -c d d -c	b -c -d -d -c
	0 -c d -d c	0 -c -d d c
(1,1,9,9)	a -c d d -c	b -d -c -c -d
	-c -c c -c c	-d -d d -d d
(1,2,2,4)	a 0 d d 0	0 0 d -d 0
	b -c 0 0 0	c b 0 0 0
(1,2,2,9)	a -d 0 0 -d	d -d d 0 0
	b -c d d 0	c b 0 -d -d
(1,2,3,6)	a 0 d d 0	b -c 0 -d 0
	b c 0 d 0	c 0 -d d 0
(1,2,4,8)	a 0 d d 0	b -c d -d -c
	b 0 -d d 0	d d c 0 c
(1,2,8,9)	a -d c c -d	d -d d -c -c
	c -b d d c	b c -c -d -d
(1,4,4,4)	a 0 b b 0	0 0 b -b 0
	0 -c d d c	0 -c d -d -c
(1,4,5,5)	a -d 0 0 -d	-d -c 0 0 c
	c -d b b d	0 -c b -b -c
(1,5,5,9)	a -b c c -b	-c -b d d b
	b -d c -c -d	-d -d d -d d
(2,2,2,2)	a -b 0 0 0	b a 0 0 0
	c -d 0 0 0	d c 0 0 0
(2,2,2,8)	a -d b d 0	a d -b -d 0
	c 0 d 0 d	c 0 -d 0 -d
(2,2,4,4)	a -b 0 0 0	b a 0 0 0
	0 -c d d c	0 -c d -d -c
(2,2,4,9)	a -b d d 0	a b d d 0
	0 -d c -c -d	d -d c c d
(2,2,8,8)	a -d c -d -c	a d -c d c
	b -c -d -c d	b c d c -d
(2,3,4,6)	b -d a 0 0	b -d -a 0 0
	-b -d c c d	0 -d c -c -d
(2,3,6,9)	b -d c -a -d	a -d -d b -c
	-b -d -d -c c	d -d -c -c d
(2,4,4,8)	c 0 b -d d	c 0 b d -d
	b -a -c -d -d	b a -c d d
(2,5,5,8)	c -b d d b	a -c d -d -c
	-a -b d -d -b	-b -c d d c
(3,3,3,3)	a -b c 0 0	a b 0 -d 0
	a 0 -c d 0	b c d 0 0
(3,3,6,6)	0 -d -a -c -b	0 -d a c -b
	b -c d -d -c	a -c d d c
(4,4,4,4)	0 -a b b a	0 -a b -b -a
	0 -c d d c	0 -c d -d -c
(4,4,5,5)	d -c a a c	0 -d a -a -d
	0 -c b -b -c	-c -d b b d
(5,5,5,5)	a -b b -d -d	-b -a a -c -c
	d -c c a a	-c -d d b b
(1,1,13)	a -c -c -c -c	0 -c -c c -c
	b -c 0 0 -c	0 -c c -c 0
(1,2,17)	a -c -c -c -c	b -c -c c -c
	b c c -c c	c c -c c -c

(1,2,11)	a	0	c	c	0	b	0	c	c	-c
	b	0	-c	-c	c	0	-c	0	-c	c
(1,3,14)	a	-c	-c	-c	-c	-b	-c	c	-c	0
	c	-c	c	-b	-c	c	-c	-c	0	b
(1,4,13)	a	-c	-c	-c	-c	0	-c	-c	c	-c
	0	-c	b	-b	-c	b	-c	c	-c	-b
(1,6,11)	a	-c	b	b	-c	c	-c	b	-b	-c
	c	b	c	-c	0	c	0	c	c	b
(1,8,11)	a	-c	-b	-b	-c	-c	-c	b	-b	-c
	c	b	c	-c	b	c	-b	c	c	b
(2,5,7)	c	-c	-c	0	-a	a	-c	b	b	0
	b	-b	0	-c	0	c	b	0	-c	0
(3,6,8)	0	-b	c	b	-c	0	-b	c	-a	c
	a	-b	-c	0	-c	a	b	c	b	-c
(7,10)	0	-a	a	b	-b	b	-a	a	a	a
	0	-a	a	a	b	b	0	b	b	a

## Order 28

Design	A, C							B, D						
(1,1,1,1)	a	0	0	0	0	0	0	b	0	0	0	0	0	0
	c	0	0	0	0	0	0	d	0	0	0	0	0	0
(1,1,1,4)	a	0	0	0	0	0	0	b	0	0	0	0	0	0
	d	-c	-d	0	0	0	0	d	0	d	0	0	0	0
(1,1,1,9)	d	-a	-d	0	0	0	0	d	-b	-d	0	0	0	0
	d	0	c	0	-d	0	0	d	0	d	0	d	0	0
(1,1,1,16)	a	-d	d	d	d	d	-d	b	0	d	0	0	d	0
	c	0	d	0	0	d	0	0	-d	d	d	d	-d	d
(1,1,1,25)	a	-d	d	d	d	d	-d	b	-d	d	d	d	d	-d
	c	-d	d	d	d	d	-d	-d	-d	d	-d	d	-d	d
(1,1,2,2)	a	0	0	0	0	0	0	b	0	0	0	0	0	0
	c	-d	0	0	0	0	0	c	d	0	0	0	0	0
(1,1,2,8)	d	-a	-d	0	0	0	0	d	-b	-d	0	0	0	0
	d	-c	d	0	0	0	0	d	c	d	0	0	0	0
(1,1,2,18)	a	-b	b	b	b	b	-b	c	-b	b	b	b	b	-b
	d	-b	b	0	b	0	0	-d	-b	b	0	b	0	0
(1,1,4,4)	a	0	0	0	0	0	0	b	0	0	0	0	0	0
	c	-c	d	d	0	0	0	d	-d	-c	-c	0	0	0
(1,1,4,9)	a	-d	d	d	d	d	-d	0	-d	d	0	d	0	0
	b	0	0	-c	-c	0	0	0	0	0	-c	c	0	0
(1,1,4,16)	b	0	b	0	b	0	b	b	0	b	-a	-b	0	-b
	b	-c	-b	0	-b	-c	b	b	-c	-b	-d	b	c	-b
(1,1,5,5)	a	0	0	0	0	0	0	b	0	0	0	0	0	0
	c	-c	-c	-d	0	-d	0	d	-d	-d	c	0	c	0
(1,1,8,8)	c	-d	a	d	-c	0	0	-c	-d	b	d	c	0	0
	c	-d	0	-d	c	0	0	c	d	0	d	c	0	0
(1,1,9,9)	a	-c	c	c	c	c	-c	0	-c	c	0	c	0	0
	b	-d	d	d	d	d	-d	0	-d	d	0	d	0	0
(1,1,10,10)	d	-a	a	a	a	a	-a	c	-b	b	b	b	b	-b
	-a	-b	b	0	b	0	0	b	-a	a	0	a	0	0
(1,1,13,13)	-a	-b	b	-a	b	-a	a	-b	a	-a	-b	-a	-b	b
	c	-a	a	a	a	a	-a	d	-b	b	b	b	b	-b
(1,2,2,4)	b	-a	-b	0	0	0	0	b	0	b	0	0	0	0
	c	-d	0	0	0	0	0	c	d	0	0	0	0	0
(1,2,2,9)	a	-d	d	d	d	d	-d	0	-d	d	0	d	0	0
	b	-c	0	0	0	0	0	b	c	0	0	0	0	0
(1,2,2,16)	a	-d	d	d	d	d	-d	b	0	d	-c	0	d	0
	b	0	d	c	0	d	0	0	-d	d	d	d	-d	d
(1,2,3,6)	a	-b	c	0	0	0	0	a	-b	-c	0	0	0	0
	b	a	b	0	0	0	0	b	-d	-b	0	0	0	0

(1,2,4,8)	c -a -c 0 0 0 0	c 0 c 0 0 0 0
	d -b -d -d 0 -d 0	d -b -d d 0 d 0
(1,2,8,9)	a -d d d d d -d	0 -d d 0 d 0 0
	-b -b b -c b 0 0	-b -b b c b 0 0
(1,3,6,8)	-c -c c 0 c -a b	c c -c 0 -c -a b
	b a b 0 0 0 0	b -d -b 0 0 0 0
(1,4,4,4)	b -a -b 0 0 0 0	b 0 b 0 0 0 0
	c -c d d 0 0 0	d -d -c -c 0 0 0
(1,4,4,9)	a -d d d d d -d	0 -d d 0 d 0 0
	c -c b b 0 0 0	b -b -c -c 0 0 0
(1,4,5,5)	b -a -b 0 0 0 0	b 0 b 0 0 0 0
	c -c -c -d 0 -d 0	d -d -d c 0 c 0
(1,5,5,9)	a -d d d d d -d	0 -d d 0 d 0 0
	b -b -b -c 0 -c 0	c -c -c b 0 b 0
(2,2,2,2)	a -b 0 0 0 0 0	a b 0 0 0 0 0
	c -d 0 0 0 0 0	c d 0 0 0 0 0
(2,2,8,2)	a -b 0 0 0 0 0	a b 0 0 0 0 0
	c -d -c -c 0 -c 0	c -d -c c 0 c 0
(2,2,2,18)	a -d -d 0 b -d -d	a -d -d 0 -b -d -d
	c -d d -d d d 0	-c -d d -d d d 0
(2,2,4,4)	a -b 0 0 0 0 0	a b 0 0 0 0 0
	c -c d d 0 0 0	d -d -c -c 0 0 0
(2,2,4,16)	a -b -a -a c -a 0	a -b -a -a -c -a 0
	a -b -a a d a 0	a -b -a a -d a 0
(2,2,5,5)	a -b 0 0 0 0 0	a b 0 0 0 0 0
	c -c -c -d 0 -d 0	d -d -d c 0 c 0
(2,2,8,8)	a -b -a -a 0 -a 0	a -b -a a 0 a 0
	c -d -c -c 0 -c 0	c -d -c c 0 c 0
(2,2,9,9)	d -b -d -c a c 0	d -b -d c -a -c 0
	d -c 0 -c -d -c 0	-c -d 0 -d c -d 0
(2,2,10,10)	c -c -c -d a -d 0	c -c -c -d -a -d 0
	d -d -d c b c 0	d -d -d c -b c 0
(2,3,4,6)	a -d 0 d a 0 0	a -d c -d -a 0 0
	b -c -d 0 0 0 0	-b -c -d 0 0 0 0
(2,4,4,8)	a -b -a -a 0 -a 0	a -b -a a 0 a 0
	c -c d d 0 0 0	d -d -c -c 0 0 0
(2,4,6,12)	a -b c -a b c 0	a -b c a -b -c 0
	b a b -b d b 0	b a b b -d -b 0
(2,5,5,8)	a -d -a -a 0 -a 0	a -d -a a 0 a 0
	c -c -c -b 0 -b 0	b -b -b c 0 c 0
(2,8,8,8)	a -a b b c -d -c	a -a b b -c d c
	a a b -b c 0 c	a a b -b -c 0 -c
(3,3,3,3)	a -b -c 0 0 0 0	a b 0 -d 0 0 0
	a 0 c d 0 0 0	b -c d 0 0 0 0
(3,3,3,12)	-c -c c 0 c -a b	c c -c -d -c -a 0
	c c -c d -c 0 b	0 0 0 d 0 -a -b
(3,3,6,6)	a -d b d a 0 0	a -d c -d -a 0 0
	c d a 0 -b 0 0	c d -a 0 b 0 0
(3,4,6,8)	-c -c c 0 c -a b	c c -c 0 -c -a b
	d -b 0 b d 0 0	-d -b -a -b d 0 0
(4,4,4,4)	a -b c -d 0 0 0	a b c d 0 0 0
	a -b -c d 0 0 0	a b -c -d 0 0 0
(4,4,4,16)	c -d -c -c a -c b	c -d -c -c -a -c -b
	c -d -c c a c -b	c -d -c c -a c b
(4,4,5,5)	a -a b b 0 0 0	b -b -a -a 0 0 0
	c 0 c -d d d 0	d 0 d c -c -c 0
(4,4,8,8)	a -a b b c -d 0	a -a b b -c d 0
	a a b -b c d 0	a a b -b -c -d 0
(4,4,10,10)	b -c a -c d -d -d	b c a c -d d d
	b -d -a -d -c c c	b d -a d c -c -c

(5,5,5,5)	a -a -a -b 0 -b 0	-b b b -a 0 -a 0
	-c c c d 0 d 0	-d d d -c 0 -c 0
(6,6,6,6)	a -a b b c -d 0	-b b a a d c 0
	-c c -d -d a -b 0	-d d c c -b -a 0
(7,7,7,7)	a -a -a -b c -b d	-b b b -a d -a -c
	-c c c d a d b	-d d d -c -b -c a
(1,2,22)	a -b 0 -b b -b -b	a b 0 b -b b b
	0 b b b b -b b	c -b b b b b -b
(1,3,24)	a -c -c -c -c -c -c	b -c -c c -c c -c
	b c -c -c c -c c	b c c -c -c -c c
(1,4,20)	a -b b b b b -b	c c b -b b -b 0
	0 -b b b -b -b b	c 0 -b -b -b -b c
(1,6,12)	b b -b 0 -b -a a	-b -b b 0 b -a 0
	-b -b b 0 b 0 a	c 0 0 -a -a 0 0
(1,6,18)	c -a a -b -b a -a	-b b a a -a -a 0
	a -a a a a -b 0	a -a -a -a -b -a 0
(1,6,21)	c -b -b -b -b -b -b	a -b b -b b b -b
	a a b -b -a -b b	a -a b b -b -b b
(1,9,13)	a -b b b b b -b	0 -b b 0 b 0 0
	0 -c -c -c c c c	c -c c c -c -c c
(1,10,14)	c b -b -b -b -b b	0 b a -a a a a
	0 -b -a -b a -b a	0 -b b -a -b a b
(2,2,13)	a -b 0 0 0 0 0	a b 0 0 0 0 0
	0 -c -c -c c c c	c -c c c -c -c c
(2,7,19)	c -a a -a -a -b -a	-c -a b -a -a -a -a
	b b a -a -b -a a	b -b a a -a -a a
(2,8,13)	-b -b b -c b 0 0	-b -b b c b 0 0
	0 -a -a -a a a a	a -a a a -a -a a
(4,4,18)	a b -c b -b -b -b	a -b -c -b b b b
	a b -b -b b -c 0	a -b b b -b -c 0
(5,5,13)	a -a -a -b 0 -b 0	b -b -b a 0 a 0
	0 -c -c -c c c c	c -c c c -c -c c
(3,23)	-a 0 b -b b b b	a b b -b b b b
	a -b b b b b 0	b -b b -b b b -b
(4,19)	b -b 0 -a 0 a 0	b b a a a a a
	0 -a a 0 -a -a a	a -a a -a a a -a
(5,21)	b a a -b -b -a a	b -b a a -a -a -a
	a -a -a a -a -a 0	a -a a -a -a -a 0
(5,23)	a -a -a b b -b b	-a -b -a -b -b -b
	b -b b -b b b -b	b -b b b b -b -b
(6,17)	b b a -a a -a -a	b -b a -a -a a 0
	b -a -a -a a a a	b 0 -a 0 0 0 -a
(6,20)	b -a b -a -a 0 a	b -a -b -a 0 a -a
	b -a a a -a -a -a	b a -a a -a -a -a
(7,10)	a 0 0 -b 0 0 0	b a a 0 0 -a 0
	a 0 -b -b b 0 b	-b -b b 0 b a -a
(7,15)	b -a b -a -b 0 a	b a 0 -b 0 0 0
	b a a a 0 -a a	b a -a a a -a -a
(8,17)	a a a a -a -a 0	a -a b -b b b 0
	b a -a a b 0 a	b -a a a a -a -b
(9,16)	b -b b -a b a -b	b -a a -a -b -a 0
	b b 0 -a a a -a	a a a a -a -a 0
(9,17)	a a a a -a -a 0	a -a -a b -a a b
	a -a -b -b a -a 0	a -b -a -b b -b -b
(11,12)	a a a -a 0 0 0	-b -a a -a -a a a
	a -b a -b b b -b	b -b -b -b 0 -b 0
(11,15)	b -b -b -b 0 -b -a	b -b -b b 0 b -a
	b -a a a -a -a a	a -a a -a -a -a -a
(11,17)	b b b -b b -a -a	b b -b b b a -a
	b -a -a a -a a a	a -a a a a -a -a

(12,14)	b	a	b	-b	-b	-a	-a	b	-a	b	-a	b	b	a
	b	-b	-a	a	a	0	-a	a	-a	b	a	-b	a	0