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THE NUMBER OF MUTUALLY ORTHOGONAL LATIN  
SQUARES - A TABLE UP TO ORDER 10000

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The number of mutually orthogonal Latin squares - a table up to order 10000

by

A.E. Brouwer

ABSTRACT

We give a table of lower bounds for  $N(v)$ , the maximum number of mutually orthogonal Latin squares of order  $v$ , for  $v < 10000$ .

Some new results are  $n_7 \leq 1726$ ,  $n_8 \leq 7464$ ,  $N(154) \geq 8$ ,  $N(262) \geq 8$ .

KEY WORDS AND PHRASES: *mutually orthogonal Latin squares.*



## EXPLANATION

Let  $N(v)$  be the maximum number of mutually orthogonal Latin squares of order  $v$ . Below we give a table of lower bounds for  $N(v)$  found by application of the following propositions.

PROPOSITION 0.

$$N(0) = N(1) = +\infty,$$

$$N(q) = q-1 \text{ if } q \text{ is a primepower.}$$

PROPOSITION 1.

$$N(v) \geq 1 \text{ for all } v.$$

PROPOSITION 2.

$$N(uv) \geq N(u) \cdot N(v) \quad [\text{MacNeish}].$$

PROPOSITION 3.

$$N(12) \geq 5 \quad [\text{Johnson, Dulmage \& Mendelsohn}],$$

$$N(15) \geq 4 \quad [\text{Schellenberg, Van Rees \& Vanstone}],$$

$$N(36) \geq 4, N(46) \geq 4, N(50) \geq 6 \quad [\text{Wilson}],$$

$$N(39) \geq 4, N(48) \geq 4, N(55) \geq 5, N(56) \geq 7 \quad [\text{Mills}],$$

$$N(82) \geq 8, N(100) \geq 8 \quad [\text{Mullin, Schellenberg, Stinson \& Vanstone}],$$

$$N(154) \geq 8, N(262) \geq 8 \quad [\text{Brouwer}].$$

PROPOSITION 4.

$$N(v) \geq 2 \text{ for } v > 6 \quad [\text{Bose, Parker \& Shrikhande}],$$

$$N(v) \geq 3 \text{ for } v > 14 \quad [\text{Wang \& Wilson}].$$

PROPOSITION 5. *If  $k \leq N(m)+1$  then for  $1 \leq x \leq m-1$ :*

$$N(km+x) \geq \min \{N(m), N(x), N(k)-1, N(k+1)-1\} \quad [\text{Hall 13.3.8}].$$

PROPOSITION 6. *If  $0 \leq u \leq t$  then*

$$N(mt+u) \geq \min \{N(m), N(m+1), N(t)-1, N(u)\} \quad [\text{Wilson, thm. 2.3}].$$

PROPOSITION 7. *If there is a symmetric BIBD(v,k,1) then*

$$N(v) \geq N(k) \quad [\text{Van Lint 13.2.1; Raghavarao 3.4.2.1}]$$

and

$$N(k^2+1) \geq \min \{N(k), N(k+1)-1\} \quad [\text{Van Lint 13.2.2}].$$

*In particular this holds when  $k = q+1$ ,  $q$  the power of a prime.*

PROPOSITION 8. *If there is a resolvable BIBD(v,k,1) with  $r$  replications, then*

$$N(v) \geq N(k) \quad [\text{Hall 13.3.2}],$$

$$N(v+1) \geq \min \{N(k)-1, N(k+1)\}$$

[easy to see from the proof of Hall 13.3.2],

$$N(v+x) \geq \min \{N(k)-1, N(k+1)-1, N(x)\} \text{ for } 1 \leq x \leq r-2 \quad [\text{Hall 13.3.5}],$$

$$N(v+r-1) \geq \min \{N(k), N(k+1)-1, N(r-1)\} \quad [\text{ibid.}],$$

$$N(v+r) \geq \min \{N(k+1)-1, N(r)\} \quad [\text{ibid.}].$$

*In particular this holds for  $q$  a primepower and*

$$v = q^3+1, k = q+1 \quad [\text{Bose (1959); Raghavarao 3.4.2.3}],$$

or

$$v = 2^{m-1}(2^m-1), k = 2^{m-1}$$

[Bose & Shrikhande (1959); Raghavarao 3.4.2.4].

PROPOSITION 9. *If there exists a BIBD(v,k,1) then*

$$N(v-1) \geq \min \{N(k-1), N(k)-1\}$$

and

$$N(v-x) \geq \min \{N(k-x), N(k-1)-1, N(k)-1\} \text{ for } 2 \leq x \leq k \quad [\text{Hall 13.3.3}],$$

and

$$N(v-3) \geq \min \{N(k-2), N(k-1)-1, N(k)-1\} \quad [\text{Hall 13.3.4}].$$

*In particular this holds for  $q$  a primepower and*

$$v = q^2+q+1, k = q+1 \quad [\text{PG}(2,q)]$$

and

$$v = q^2, k = q \quad [\text{AG}(2,q)].$$

*If there exists a BIBD(v,k,1) with an oval of size  $m$  (i.e.,  $m$  points, no three in a block) then*

$$N(v-x) \geq \min \{N(k)-1, N(k-1)-1, N(k-2)-1\} \text{ for } 4 \leq x \leq m.$$

*In particular this holds for  $\text{PG}(2,q)$  and  $\text{AG}(2,q)$  with  $m = q+1$  (or  $m = q+2$  if  $q$  is even).*

If  $q \equiv 0$  or  $1 \pmod{3}$  then  $PG(2,q)$  contains a configuration isomorphic to  $AG(2,q)$  so that we have a pairwise balanced design on  $v-9$  points with blocks of size  $k$ ,  $k-1$  and  $k-3$ . Hence

$$N(v-9) \geq \min \{N(k)-1, N(k-1)-1, N(k-3)-1\}.$$

PROPOSITION 10 (a). If  $0 \leq u \leq t$  and  $0 \leq v \leq t$  then

$$N(mt+u+v) \geq \min \{N(m), N(m+1), N(m+2), N(u), N(v), N(t)-2\}$$

[Wilson, thm 2.4].

PROPOSITION 11 (b). If  $r > (t-1)(t-2)/2$  then

$$N(mr+t) \geq \min \{N(m), N(m+1), N(m+2), N(r)-t\} \quad [\text{Wilson, thm 2.5}].$$

If  $r$  is a primepower then the same conclusion holds when  $r \geq t$

[for: use an oval in  $PG(2,r)$ ].

If  $r \geq b+s(s-1)/2$  then

$$N(mr+b+s) \geq \min \{N(m), N(m+1), N(m+2), N(b), N(r)-s-1\} \quad [\text{Van Rees}].$$

PROPOSITION 12 (c). If  $0 < w < t$  then

$$N(mt+w) \geq \min \{N(m), N(m+1), N(m+w), N(t)-w\}$$

[Wojtas, preprint 4, thm 2.2].

PROPOSITION 13 (d).

$$N(135) \geq 7.$$

[For:  $135 = 8 \cdot 16 + 7$ ; take a  $PG(2,16)$ , i.e., a  $T[17,1;16]$ , remove one group entirely and truncate seven other groups in such a way that on each group one point remains, these seven points forming a Fano subplane of  $PG(2,16)$ . Now apply Wilson's theorem.]

PROPOSITION 14 (e). If  $0 \leq u \leq t$  and  $n = m_1(m_2t+u)$  then

$$N(n) \geq \min \{N(m_1), N(m_2+1), N(m_1m_2), N(t)-1, N(m_1u)\}$$

[Wojtas, komunikat 172, thm 2.4].

PROPOSITION 15 (f). If  $0 \leq u, v \leq t$  and  $n = m_1(m_2t+u+v)$  then

$$N(n) \geq \min \{N(m_1), N(m_2+1), N(m_2+2), N(m_1m_2), N(m_1u), N(m_1v), N(t)-2\}$$

[improved version of: Wojtas, *ibid.*, thm. 2.5].

PROPOSITION 16 (g). If  $t > (r-1)(r-2)/2$  and  $n = m_1(m_2t+r)$  then

$$N(n) \geq \min \{N(m_1), N(m_2+1), N(m_2+2), N(m_1m_2), N(t)-r\}$$

[improved version of: Wojtas, *ibid.*, thm. 2.6].

If  $t$  is a primepower the same conclusion holds as soon as  $t \geq r$  [as above].

PROPOSITION 17 (h). If  $0 \leq w \leq t$  and  $n = m_1(m_2t+w)$  then

$$N(n) \geq \min \{N(m_1), N(m_2+1), N(m_2+w)-1, N(m_1m_2), N(t)-w\}.$$

For  $w < 4$  we may replace ' $N(m_2+w)-1$ ' by ' $N(m_2+w)$ ' [Wojtas, *ibid.*, thm. 2.7].

PROPOSITION 18 (i). If  $u, v \geq 0$ ,  $u+v \leq t$  and  $n = m_1m_2t+m_1u+v$ , then

$$N(n) \geq \min \{N(m_1), N(m_2+1), N(m_1m_2), N(m_1m_2+1), N(t)-1, N(m_1u+v)\}$$

[Wojtas, *ibid.*, thm. 2.3].

PROPOSITION 19 (j). If  $n = mt+h_1+h_2+h_3$ , where  $0 \leq h_1, h_2, h_3 \leq t$ ,  $h_1 \leq h_2$ ,

$(t-h_1-1)(t-h_2) < h_3 \leq t$ , then

$$N(n) \geq \min \{N(m+1), N(m+2), N(m+3), N(h_1), N(h_2), N(h_3), N(t)-3\}$$

[Wojtas, *komunikat* 236, thm. 2].

PROPOSITION 20 (k). If  $0 \leq u+v_1 \leq t$ ,  $0 \leq v_2 \leq t$ ,  $n = m_1m_2t+m_1u+v_1+v_2$ , then

$$N(n) \geq \min \{N(m_1), N(m_1+1), N(m_2+1)-2, N(m_1m_2), N(m_1m_2+1), N(m_1m_2+2), \\ N(m_1u+v_1), N(v_2), N(t)-2\}.$$

If  $m_1 < m_2$  we may replace ' $N(m_2+1)-2$ ' by ' $N(m_2+1)-1$ '

[Wojtas, *preprint* 4, thm. 2.3].

PROPOSITION 21 (l). If  $T[k+1;t]$  and  $T[k; m_1h_1 + \dots + m_s h_s]$  and (for  $i = 1, \dots, s$ )

$T[k; m+m_i] - T[k; m_i]$  all exist, where  $h_1 + \dots + h_s = t$ , then also

$T[k; mt+m_1h_1 + \dots + m_s h_s]$  exists.

[This is a generalization of Wojtas, *komunikat* 172, thm. 2.1 and related to Horton, thm. 4.]

(It often happens that for the construction of a certain design one needs a transversal design  $T[k;v]$  with subdesign  $T[k;u]$  which is to be discarded.

What is left is a design on a set  $I_k \times X$  such that any two points with different first coordinates are in a unique block unless their second coordinates are both in  $Y$ . Here  $Y \subset X$ ,  $|Y| = u$ ,  $|X| = v$ . I call such a



configuration a  $T[k;v]-T[k;u]$ ; J.D. Horton calls it an incomplete orthogonal array  $IA(v,u,k)$ . Note that the existence of such an animal does not imply the existence of either  $T[k;v]$  or  $T[k;u]$ : I can construct  $T[6;10]-T[6;2]$ , while  $T[6;2]$  clearly cannot exist and a  $T[6;10]$  would be sensational. But we do have that if both  $T[k;u]$  and  $T[k;v]-T[k;u]$  exist, then so does  $T[k;v]$ . The above proposition gave an example of the use of such designs; the following lemma gives a few cases where we know that they exist. Certainly one can say more - while waiting for the printing of the tables (on a slow terminal) I showed  $N(694) \geq 7$  by similar methods. I hope to include tables for transversal designs with subdesigns of a given small order in a future version of this paper.)

SUBSQUARES LEMMA.

- (i)  $T[k;v]-T[k;0]$  and  $T[k;v]-T[k;1]$  exist iff  $T[k;v]$  exists.
- (ii) If  $T[k+1;t]$ ,  $T[k;m]$  and  $T[k;m+1]$  exist, then  $T[k;mt+u]-T[k;u]$  exists.
- (iii) If  $T[k;m]$  and  $T[k;n]$  exist, then  $T[k;mn]-T[k;n]$  exists.
- (iv) If  $V(m,t)$  (defined in Mullin, Schellenberg, Stinson & Vanstone, 1978) exists, then  $T[m+2;q+t]-T[m+2;t]$  exists, where  $q = mt+1$ .

[This is essentially Wilson's proposition 2 (1974b).]

Examples of vectors  $V(m,t)$  are:

$$V(4,7) = (0,1,3,7,19) \quad [\text{Wilson}],$$

$$V(4,9) = (0,1,3,2,8) \quad [\text{Wilson}],$$

$$V(6,7) = (0,1,3,16,35,26,36)$$

[Wilson proved the existence of  $T[8;50]-T[8;7]$  using a non-circulant matrix; Mullin e.a. give a circulant which is incorrect.],

$$V(8,9) = (0,1,20,70,23,59,3,8,19)$$

[Mullin, Schellenberg, Stinson & Vanstone],

$$V(8,11) = (0,1,6,56,22,35,47,23,60) \quad [\text{ibid.}],$$

$$V(7,6) = (0,1,12,27,37,16,30,35),$$

$$V(7,10) = (0,1,3,45,9,50,28,16),$$

$$V(7,16) = (0,1,3,7,82,72,93,39),$$

$$V(7,18) = (0,1,3,6,97,114,99,26),$$

$$V(7,28) = (0,1,3,6,107,187,82,12),$$

$$V(7,30) = (0,1,3,7,50,2,69,93),$$

$$V(7,34) = (0,1,3,6,10,153,234,80),$$

$$v(8,17) = (0,1,3,2,133,126,47,109,74),$$

$$v(8,29) = (0,1,4,11,94,60,85,16,198).$$

(Note that the last two lines show that  $T[10;154]$  and  $T[10;262]$  exist.)

The table gives for  $v < 10000$  either a lower bound for  $N(v)$  followed by an indication of the proposition used to obtain this estimate between square brackets (where 10, 11, ..., 21 are coded a, b, ..., l) or an entry \*\* if this lower bound exceeds 99. For  $v > 1$  this means in practice that  $v$  is a prime power and  $N(v) = v-1$ . Between square brackets we give  $k$  if  $v = p^k$  for some prime  $k$ , and 0 otherwise.

\*\*\*\*\*  
 \*  
 \* Lower bounds for N(v), \*  
 \* the number of mutually orthogonal Latin squares of order v \*  
 \* AEB, 790625 \*  
 \*  
 \*\*\*\*\*

0:	**	[0]	**	[0]	1	[0]	2	[0]	3	[0]	4	[0]	1	[0]	6	[0]	7	[0]	8	[0]
10:	2	[4]	10	[0]	5	[3]	12	[0]	2	[4]	4	[3]	15	[0]	16	[0]	3	[4]	18	[0]
20:	3	[9]	4	[7]	3	[4]	22	[0]	3	[9]	24	[0]	3	[4]	26	[0]	3	[2]	28	[0]
30:	3	[4]	30	[0]	31	[0]	3	[6]	3	[4]	4	[2]	4	[3]	36	[0]	3	[4]	4	[3]
40:	4	[2]	40	[0]	3	[4]	42	[0]	3	[2]	4	[2]	4	[3]	46	[0]	4	[3]	48	[0]
50:	6	[3]	4	[a]	3	[2]	52	[0]	4	[9]	5	[3]	7	[3]	7	[7]	5	[a]	58	[0]
60:	4	[2]	60	[0]	4	[a]	6	[9]	63	[0]	7	[7]	5	[9]	66	[0]	5	[9]	5	[9]
70:	6	[9]	70	[0]	7	[9]	72	[0]	5	[9]	5	[9]	5	[9]	6	[2]	6	[9]	78	[0]
80:	7	[9]	80	[0]	8	[3]	82	[0]	6	[6]	6	[6]	6	[6]	6	[a]	7	[2]	88	[0]
90:	6	[j]	7	[c]	6	[6]	6	[a]	6	[a]	6	[5]	7	[6]	96	[0]	6	[6]	8	[2]
100:	8	[3]	**	[1]	6	[6]	**	[1]	7	[2]	7	[6]	6	[a]	**	[1]	6	[a]	**	[1]
110:	6	[a]	6	[5]	7	[6]	**	[1]	6	[a]	7	[6]	6	[b]	8	[2]	6	[b]	6	[2]
120:	7	[8]	**	[2]	6	[a]	6	[6]	6	[a]	**	[3]	6	[6]	**	[1]	**	[7]	7	[6]
130:	6	[6]	**	[1]	6	[6]	7	[c]	6	[6]	7	[d]	7	[8]	**	[1]	6	[a]	**	[1]
140:	6	[6]	7	[6]	6	[6]	10	[2]	8	[2]	7	[6]	6	[6]	7	[6]	6	[a]	**	[1]
150:	6	[6]	**	[1]	7	[2]	8	[2]	8	[3]	7	[c]	6	[a]	**	[1]	6	[a]	6	[5]
160:	7	[6]	7	[6]	6	[6]	**	[1]	6	[b]	7	[6]	6	[a]	**	[1]	7	[6]	**	[2]
170:	6	[6]	8	[2]	6	[6]	**	[1]	6	[6]	6	[2]	10	[2]	9	[6]	6	[6]	**	[1]
180:	6	[6]	**	[1]	6	[6]	6	[6]	7	[2]	8	[6]	6	[6]	10	[2]	6	[6]	7	[c]
190:	6	[6]	**	[1]	7	[6]	**	[1]	6	[6]	7	[6]	6	[6]	**	[1]	6	[6]	**	[1]
200:	7	[2]	7	[6]	6	[6]	7	[6]	6	[6]	7	[c]	6	[6]	8	[2]	12	[2]	11	[6]
210:	6	[6]	**	[1]	6	[6]	7	[6]	6	[6]	7	[c]	7	[2]	8	[6]	6	[6]	10	[6]
220:	6	[6]	12	[2]	6	[6]	**	[1]	7	[6]	8	[2]	6	[6]	**	[1]	6	[6]	**	[1]
230:	6	[6]	7	[c]	7	[2]	**	[1]	6	[6]	7	[6]	6	[6]	7	[c]	6	[a]	**	[1]
240:	7	[6]	**	[1]	6	[6]	**	[5]	6	[6]	7	[6]	6	[6]	12	[2]	7	[2]	7	[6]
250:	6	[a]	**	[1]	6	[a]	10	[2]	6	[a]	7	[6]	**	[8]	**	[1]	6	[a]	12	[c]
260:	6	[6]	8	[2]	8	[3]	**	[1]	7	[9]	8	[9]	6	[6]	10	[9]	6	[6]	**	[1]
270:	6	[6]	**	[1]	15	[9]	16	[7]	6	[a]	13	[c]	6	[6]	**	[1]	6	[6]	9	[c]
280:	7	[9]	**	[1]	6	[6]	**	[1]	6	[6]	12	[9]	6	[6]	7	[6]	15	[9]	**	[2]
290:	6	[6]	6	[6]	6	[a]	**	[1]	6	[6]	6	[6]	7	[2]	10	[2]	6	[6]	12	[2]
300:	6	[6]	7	[c]	6	[6]	6	[5]	15	[2]	15	[6]	6	[6]	**	[1]	6	[6]	7	[6]
310:	6	[6]	**	[1]	7	[5]	**	[1]	6	[6]	10	[5]	6	[6]	**	[1]	6	[6]	10	[2]
320:	15	[6]	15	[6]	6	[a]	16	[2]	6	[6]	12	[2]	6	[6]	7	[6]	7	[2]	7	[6]
330:	6	[6]	**	[1]	6	[6]	8	[2]	6	[a]	6	[5]	7	[6]	**	[1]	6	[6]	7	[6]
340:	6	[6]	10	[2]	9	[6]	**	[3]	7	[2]	7	[6]	6	[6]	**	[1]	6	[6]	**	[1]
350:	8	[6]	12	[2]	10	[2]	**	[1]	6	[6]	7	[6]	6	[6]	7	[6]	6	[6]	**	[1]
360:	7	[6]	**	[2]	6	[6]	7	[6]	6	[a]	7	[6]	6	[6]	**	[1]	15	[2]	15	[6]
370:	6	[6]	15	[c]	6	[6]	**	[1]	6	[6]	15	[c]	7	[2]	13	[c]	6	[6]	**	[1]
380:	6	[6]	12	[5]	6	[6]	**	[1]	15	[6]	15	[6]	6	[6]	15	[6]	6	[6]	**	[1]
390:	6	[6]	16	[2]	7	[2]	7	[8]	6	[6]	7	[6]	6	[6]	**	[1]	6	[6]	7	[6]
400:	15	[2]	**	[1]	6	[6]	15	[c]	11	[6]	7	[6]	6	[6]	15	[c]	7	[5]	**	[1]
410:	6	[6]	13	[c]	8	[6]	12	[5]	10	[6]	9	[c]	15	[6]	15	[6]	6	[6]	**	[1]
420:	6	[6]	**	[1]	6	[6]	15	[6]	7	[2]	16	[2]	6	[6]	7	[c]	6	[6]	7	[6]
430:	6	[6]	**	[1]	15	[2]	**	[1]	6	[6]	15	[c]	6	[6]	18	[2]	6	[6]	**	[1]
440:	7	[5]	15	[c]	6	[6]	**	[1]	6	[6]	13	[c]	6	[6]	11	[c]	15	[6]	**	[1]
450:	6	[2]	15	[6]	6	[6]	7	[6]	6	[6]	15	[6]	7	[2]	**	[1]	6	[6]	16	[2]
460:	6	[6]	**	[1]	6	[6]	**	[1]	15	[2]	15	[6]	6	[6]	**	[1]	6	[6]	7	[c]
470:	6	[6]	15	[c]	7	[2]	15	[c]	6	[5]	18	[2]	6	[6]	15	[c]	6	[6]	**	[1]
480:	15	[6]	15	[6]	6	[6]	15	[6]	6	[6]	7	[6]	6	[6]	**	[1]	7	[2]	15	[6]
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9350: 12 [f] 15 [6] 30 [6] 46 [2] 30 [6] 15 [5] 16 [5] 15 [6] 13 [5] 48 [2]  
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9370: 11 [6] \*\* [1] 30 [6] 15 [6] 9 [6] 15 [2] 31 [2] \*\* [1] 11 [6] 82 [2]  
9380: 9 [6] 15 [6] 11 [6] 17 [1] 9 [6] 15 [6] 12 [e] 15 [6] 9 [6] 40 [2]  
9390: 11 [6] \*\* [1] 15 [2] 15 [6] 11 [6] 15 [6] 11 [6] \*\* [1] 9 [6] 15 [6]

9400: 15 [e] 15 [6] 9 [b] \*\* [1] 9 [6] 15 [6] 11 [6] 22 [2] 15 [6] \*\* [2]  
9410: 10 [6] 15 [6] 11 [5] \*\* [1] 10 [a] 15 [6] 10 [2] 15 [6] 11 [6] \*\* [1]  
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Some statistics:

prop0: used 1279 times (necessary: 1283)  
 0 1 2 3 4 5 6 7 8 9  
 prop2: used 13080 times (necessary: 1257)  
 28 35 40 44 45 52 60 77 88 99  
 prop3: used 13 times (necessary: 13)  
 12 15 36 39 46 48 50 55 56 82  
 prop4: used 9 times (necessary: 9)  
 10 14 18 22 26 30 34 38 42  
 prop5: used 10356 times (necessary: 637)  
 95 111 159 303 312 315 335 381 408 413  
 prop6: used 6117 times (necessary: 4452)  
 33 84 85 86 92 96 98 102 105 112  
 prop7: used 58 times (necessary: 5)  
 21 57 65 273 993  
 prop8: used 1196 times (necessary: 6)  
 120 136 393 504 528 2016  
 prop9: used 3175 times (necessary: 37)  
 20 24 54 63 66 68 69 70 72 74  
 prop10: used 370 times (necessary: 297)  
 51 58 62 87 93 94 106 108 110 114  
 prop11: used 165 times (necessary: 141)  
 116 118 164 894 1092 1140 1210 1214 1222 1270  
 prop12: used 1601 times (necessary: 1534)  
 91 133 155 189 205 215 231 237 259 275  
 prop13: used 1 time (necessary: 1)  
 135  
 prop14: used 47 times (necessary: 42)  
 1118 1242 1254 1326 1742 2774 3654 3724 3808 3914  
 prop15: used 26 times (necessary: 23)  
 1430 4598 4826 4978 5358 5928 5966 6550 6900 7018  
 prop16: used 7 times (necessary: 7)  
 4674 4902 5510 5548 6450 6726 9052  
 prop18: used 28 times (necessary: 27)  
 810 914 1034 1238 1246 1262 1442 1460 1724 3620  
 prop19: used 47 times (necessary: 46)  
 90 796 1102 1230 1396 1400 1412 1570 1702 1704  
 prop20: used 24 times (necessary: 21)  
 950 1076 1084 1086 1094 1110 1114 1126 1132 1420  
 prop21: used 182 times (necessary: 162)  
 650 652 662 666 670 682 684 692 700 710

nmax(d):

2 6  
 3 14  
 4 52  
 5 62  
 6 76  
 7 1726  
 8 7464

2 squares not known

2 6

3 squares not known

2 3 6 10 14

4 squares not known

2 3 4 6 10 14 18 20 22 24  
26 28 30 33 34 38 42 44 52

5 squares not known

2 3 4 5 6 10 14 15 18 20  
21 22 24 26 28 30 33 34 35 36  
38 39 40 42 44 45 46 48 51 52  
54 60 62

6 squares not known

2 3 4 5 6 10 12 14 15 18  
20 21 22 24 26 28 30 33 34 35  
36 38 39 40 42 44 45 46 48 51  
52 54 55 58 60 62 66 68 69 74  
75 76

7 squares not known

2 3 4 5 6 7 10 12 14 15  
18 20 21 22 24 26 28 30 33 34  
35 36 38 39 40 42 44 45 46 48  
50 51 52 54 55 58 60 62 63 66  
68 69 70 74 75 76 77 78 84 85  
86 87 90 92 93 94 95 98 102 106  
108 110 111 114 116 118 119 122 123 124  
126 130 132 134 138 140 142 146 148 150  
156 158 159 162 164 166 170 172 174 175  
178 180 182 183 186 188 190 194 196 198  
202 204 206 210 212 214 218 220 222 226  
228 230 234 236 238 242 244 246 250 252  
254 258 260 266 268 270 274 276 278 282  
284 286 290 291 292 294 295 298 300 302  
303 306 308 310 314 316 318 322 324 326  
330 332 334 335 338 340 346 348 354 356  
358 362 364 366 370 372 374 378 380 382  
386 388 390 394 396 398 402 406 410 418  
420 422 426 428 430 434 436 438 442 444  
446 450 452 454 458 460 462 466 468 470  
474 476 478 482 484 486 490 492 494 498  
500 506 508 510 514 516 518 522 524 526  
530 532 534 542 546 548 550 554 556 558  
562 564 566 570 572 574 578 580 582 586  
588 594 596 604 610 612 614 618 620 622  
626 628 630 634 636 638 642 644 646 654

658	660	668	674	676	678	686	690	694	698
702	706	708	716	718	734	740	742	748	750
754	756	758	762	764	766	770	772	774	778
780	802	814	820	826	836	844	866	868	876
982	1012	1020	1022	1182	1190	1198	1206	1258	1718
1726									

8 squares not known

2	3	4	5	6	7	8	10	12	14
15	18	20	21	22	24	26	28	30	33
34	35	36	38	39	40	42	44	45	46
48	50	51	52	54	55	56	57	58	60
62	63	65	66	68	69	70	72	74	75
76	77	78	80	84	85	86	87	88	90
91	92	93	94	95	96	98	102	104	105
106	108	110	111	112	114	115	116	118	119
120	122	123	124	126	129	130	132	133	134
135	136	138	140	141	142	145	146	147	148
150	152	155	156	158	159	160	161	162	164
165	166	168	170	172	174	175	178	180	182
183	184	186	188	189	190	192	194	195	196
198	200	201	202	203	204	205	206	210	212
213	214	215	216	218	220	222	224	226	228
230	231	232	234	235	236	237	238	240	242
244	245	246	248	249	250	252	254	255	258
260	264	266	268	270	274	276	278	280	282
284	286	287	290	291	292	294	295	296	298
300	301	302	303	306	308	309	310	312	314
316	318	322	324	326	327	328	329	330	332
334	335	336	338	339	340	344	345	346	348
354	355	356	357	358	360	362	363	364	365
366	370	372	374	376	378	380	382	386	388
390	392	393	394	395	396	398	399	402	405
406	408	410	418	420	422	424	426	427	428
429	430	434	436	438	440	442	444	446	450
452	453	454	456	458	460	462	466	468	469
470	472	474	476	478	482	484	485	486	488
490	492	494	495	498	500	501	504	506	508
510	514	516	518	520	522	524	526	530	532
534	542	545	546	548	550	552	553	554	555
556	558	560	561	562	564	565	566	567	568
570	572	573	574	578	579	580	581	582	584
585	586	588	591	594	596	597	604	610	612
614	616	618	620	622	626	627	628	630	632
633	634	635	636	638	640	642	644	645	646
648	650	651	652	654	655	658	660	662	664
666	668	670	674	676	678	680	682	684	686
690	692	694	696	698	700	702	706	708	710
712	716	718	728	734	735	740	741	742	744
745	746	748	749	750	754	756	758	760	762
764	766	770	772	774	778	780	782	790	796
802	804	806	808	810	814	818	820	822	824
826	828	834	836	840	842	844	845	852	858
866	868	870	872	874	876	878	882	886	888
890	894	896	898	904	906	914	920	921	930
932	933	934	935	936	938	939	940	942	946
948	950	952	954	956	964	966	968	982	994
996	1000	1006	1012	1016	1018	1020	1022	1026	1028
1032	1034	1036	1038	1042	1044	1046	1050	1052	1058
1059	1060	1068	1070	1074	1076	1080	1082	1084	1086
1092	1094	1096	1102	1106	1108	1110	1112	1114	1116
1118	1122	1124	1126	1128	1130	1132	1134	1135	1138

1140	1141	1142	1144	1146	1150	1154	1162	1180	1182
1186	1188	1190	1192	1194	1196	1198	1202	1204	1206
1208	1210	1212	1214	1218	1220	1222	1224	1226	1228
1230	1234	1236	1238	1240	1242	1244	1245	1246	1248
1252	1253	1254	1258	1260	1262	1263	1266	1270	1274
1276	1286	1292	1304	1324	1326	1332	1336	1338	1348
1354	1368	1372	1412	1415	1416	1418	1419	1420	1422
1426	1428	1430	1432	1434	1436	1438	1442	1444	1446
1448	1450	1452	1454	1460	1462	1464	1478	1492	1496
1502	1508	1509	1510	1512	1514	1515	1516	1518	1522
1526	1527	1534	1576	1580	1592	1614	1620	1622	1624
1626	1628	1630	1638	1640	1642	1646	1650	1658	1678
1718	1720	1722	1724	1726	1734	1736	1738	1740	1742
1746	1750	1752	1754	1756	1758	1762	1764	1766	1768
1770	1772	1774	1780	1782	1784	1786	1788	1800	1802
1804	1806	1814	1816	1818	1820	1822	1836	1926	1930
1935	1946	1948	1954	1956	1958	1960	1962	1964	1966
1970	1972	1974	1976	1982	1986	1988	1992	2004	2005
2008	2010	2022	2068	2072	2074	2076	2092	2122	2134
2140	2150	2152	2154	2156	2158	2164	2166	2174	2182
2184	2186	2246	2266	2318	2326	2328	2332	2338	2340
2343	2348	2398	2402	2404	2406	2408	2410	2418	2420
2428	2436	2438	2446	2454	2456	2566	2568	2588	2658
2660	2662	2664	2668	2670	2722	2732	2740	2742	2744
2748	2750	2758	2764	2766	2774	2780	2794	2798	2814
2822	2836	2844	2846	2860	2862	2866	2870	2936	2942
2950	2952	2954	2956	2958	2966	2972	2974	2984	2988
2994	3062	3064	3118	3124	3126	3128	3130	3134	3258
3270	3278	3286	3288	3320	3434	3464	3466	3470	3560
3566	3580	3596	3608	3614	3622	3624	3626	3628	3630
3640	3642	3644	3662	3734	3736	3738	3740	3742	3750
3754	3756	3758	3766	3772	3790	3796	3806	3930	3932
4136	4138	4152	4204	4206	4210	4216	4218	4228	4230
4232	4236	4242	4246	4252	4254	4394	4414	4428	4472
4484	4488	4508	4520	4526	4588	4602	4738	4846	4850
5038	5052	5068	5420	5564	5740	5746	5912	6184	6328
7384	7388	7464							

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Added in proof

Extensions of the subsquare lemma have dramatic effect on the strength of proposition 21(1). I can now prove that

$$n_7 \leq 836 \text{ and } n_8 \leq 3758.$$

Other improvements are:

- $N(v) \geq 7$  for  $v = 514, 586, 658, 668, 674, 676, 686, 698, 706, 716, 718, 740, 742, 748, 754, 756, 758, 766, 770, 772, 778, 802, 820, 844, 866, 868, 876, 982, 1012, 1020, 1022, 1182, 1190, 1198, 1206, 1258, 1718, 1726.$
- $N(v) \geq 8$  for  $v = 640, 964, 1180, 1234, 1516, 1816, 1948, 1956, 1958$  etc.
- $N(v) \geq 9$  for  $v = 1210, 1320, 1428, 1844, 1864, 1929, 1974$  etc.

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