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On the number of transversals in a class of Latin squares

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Abstract
Denote by $A^k_p$ the Latin square of order $n = p^k$ formed by the Cayley table of the additive group $(\mathbb{Z}_{p^k}^+, +)$, where $p$ is an odd prime and $k$ is a positive integer. It is shown that for each $p$ there exists $Q > 0$ such that for all sufficiently large $k$, the number of transversals in $A^k_p$ exceeds $(nQ)^{\frac{n}{p^k-1}}$.

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1 Introduction

Several recent papers have addressed the issue of bounds on the numbers of transversals in Latin squares. So, suppose that $S$ is a Latin square. Denote by $T(S)$ the number of transversals in $S$, and put

$$T(n) = \max\{T(S) : S \text{ is a Latin square of order } n\}.$$

It was shown by McKay, McLeod and Wanless [4] that for $n \geq 5$, $15^{n/5} \leq T(n) \leq 0.6135n!\sqrt{n}$.

The Cayley table of any finite group forms a Latin square, and such squares are called group-based. Let $A_n$ denote the cyclic Latin square of order $n$, that is the square formed by the Cayley table of the cyclic group $(\mathbb{Z}_n, +)$. If $n$ is even then $T(A_n) = 0$, but for odd $n$ it was conjectured by Vardi [6] that there exist positive constants $c$ and $d$ such that $c^n n! \leq T(A_n) \leq d^n n!$. Subsequently Cavenagh and Wanless [1] proved that for all sufficiently large $n$, $T(A_n) > (3.246)^n$, and this appears to remain the best lower bound for any class of group-based Latin squares obtained to date.

More recently, Taranenko [5] proved that $T(n) \leq [(1 + o(1)) \frac{n}{\ln n}]^n$, while Glebov and Luria [3] have shown that $T(n) \geq [(1 - o(1)) \frac{n}{\ln n}]^n$. The latter result is based on a probabilistic argument employing random Latin squares. These more recent results lend credence to Vardi’s conjecture but do not address group-based squares directly.

In the current paper we take $p$ to be an odd prime and $k$ to be a positive integer. Then the Cayley table of the additive group $(\mathbb{Z}_p^k, +)$ forms a Latin square of order $n = p^k$ which we denote by $A_{p^k}$. We will assume that this square has its rows and columns labelled in the natural way by elements of $\mathbb{Z}_p^k$ represented as $k$-vectors over $\mathbb{Z}_p$, and when $k = 1$ we write $A_p$ rather than $A_{p^1}$. We prove that, for all sufficiently large $k$, $A_{p^k}$ has more than $(nQ)^{\frac{n}{p^{k-1}}}$ transversals, where $Q > 0$ depends only on $p$ and is independent of $k$.

Note added in proof: Since drafting our current paper, our attention has been drawn to the arXiv paper [2] which claims a proof of Vardi’s conjecture.

2 Results

We start with the observation that $A_{p^k}$ has a transversal $T$ formed from its leading diagonal. We will construct a large number of transversals by carrying out transversal trades on $T$. These trades are based on the square $A_p$ and involve transversals within this square that do not contain the (row, column, entry) triple $(0, 0, 0)$. So let $T^*$ denote the number of transversals of $A_p$ that do not contain this triple. By transitivity, the number of transversals in $A_{p^k}$ that contain the triple $(0, 0, 0)$ is $T(A_{p^k})/p^k$, so the number of transversals not containing this triple is $T(A_{p^k})(1 - \frac{1}{p^k})$. In particular, $T^* = T(A_p)(1 - \frac{1}{p})$, and note rather trivially that $T(A_p) \geq p$. 

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For $k \geq 2$, the square $A_p^k$ can be partitioned into $p^2$ subarrays by writing the row labels, the column labels and the entries in the form $(z,i)$ where $z \in \mathbb{Z}_p^{k-1}$ and $i \in \mathbb{Z}_p$. This is shown schematically in Figure 1 with the row and column labels omitted.

$$A_p^k = \begin{pmatrix}
(A_p^{k-1}, 0) & (A_p^{k-1}, 1) & \ldots & (A_p^{k-1}, p - 1) \\
(A_p^{k-1}, 1) & (A_p^{k-1}, 2) & \ldots & (A_p^{k-1}, 0) \\
\vdots & \vdots & \ddots & \vdots \\
(A_p^{k-1}, p - 1) & (A_p^{k-1}, 0) & \ldots & (A_p^{k-1}, p - 2)
\end{pmatrix}$$

$$= \begin{pmatrix}
A_{0,0} & A_{0,1} & \ldots & A_{0,p-1} \\
A_{1,0} & A_{1,1} & \ldots & A_{1,p-1} \\
\vdots & \vdots & \ddots & \vdots \\
A_{p-1,0} & A_{p-1,1} & \ldots & A_{p-1,p-1}
\end{pmatrix}$$

Figure 1: Partitioning $A_p^k$.

Taken without the row and column labels inherited from $A_p^k$, the subarrays $A_{i,j}$ and $A_{i',j'}$ are identical when $i + j = i' + j'$ in $\mathbb{Z}_p$. However, we will associate each of these subarrays with their original row and column labels.

Our transversal trades will be based on copies of $A_p$, each having precisely one entry from each $A_{i,j}$. Specifically, one (row, column, entry) triple is selected from the leading diagonal of $A_{0,0}$, say $((a,0), (a,0), (2a,0))$, and one triple is selected from $A_{0,1}$ having the same row entry, say $((a,0), (b,1), (a+b,1))$. These two choices are sufficient to determine a copy of $A_p$, denoted by $A(a,b)$, as shown in Figure 2, which also shows the inherited row and column labels.

$$\begin{pmatrix}
(a,0) & (b,1) & (2b-a,2) & \ldots & (2a-b,p-1) \\
(2a,0) & (a+b,1) & (2b,2) & \ldots & (3a-b,p-1) \\
(a+b,1) & (2b,2) & (3b-a,3) & \ldots & (2a,0) \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
(3a-b,p-1) & (2a,0) & (a+b,1) & \ldots & (4a-2b,p-2)
\end{pmatrix}$$

Figure 2: The array $A(a,b)$.

Note that the row and column labels of $A(a,b)$, inherited from $A_p^k$, have the form $(rb - (r-1)a, r)$ and the entries have the form $(rb - (r-2)a, r)$, both for $r = 0, 1, \ldots, p - 1$.

The leading diagonal of $A(a,b)$ lies in the leading diagonal of $A_p^k$ and therefore this diagonal of $A(a,b)$ forms a part of the transversal $T$. There are $T^*$ transversals in $A(a,b)$ that do not contain the triple $((a,0), (a,0), (2a,0))$. If the diagonal transversal of $A(a,b)$ in $T$ is traded for any one of these $T^*$ transversals, then a new transversal in $A_p^k$ is obtained that does not contain the triple $((a,0), (a,0), (2a,0))$. Hence, for each given $a \in \mathbb{Z}_p^{k-1}$, $T^*$ distinct transversals of $A_p^k$ may be obtained for each $b \in \mathbb{Z}_p^{k-1}$. Furthermore, for two different
values \( b, b' \in \mathbb{Z}_p^{k-1} \), the arrays \( A(a, b) \) and \( A(a, b') \) only intersect in the cell \(((a, 0), (a, 0))\), and so by varying \( b \), a total of \( p^{k-1}T^* \) distinct transversals of \( A_p^k \) may be obtained that do not contain the triple \(((a, 0), (a, 0), (2a, 0))\).

In principle, we wish to carry out these trades sequentially for as many values of \( a \) as is possible. The obstacle is that having carried out a trade using \( A(a, b) \), and having chosen \( a' \neq a \), the choice of \( b' \) is constrained by the need to ensure that \( A(a', b') \) avoids the rows, columns and entries of \( A(a, b) \). So suppose that trades have already been made using \( c-1 \) choices of \((a, b)\) and that a \( c^{th} \) choice is to be made. If \((a,b)\) defines one of the previous choices and \((a', b')\) is the proposed \( c^{th} \) choice, with \( a' \neq a \), then to ensure that rows and columns do not clash it is necessary and sufficient that \((r'r' - (r' - 1)a', r') \) and \((rb - (r-1)a, r)\) are unequal for all \( r, r' = 0, 1, \ldots, p - 1 \). But these two quantities can only be equal if \( r' = r \), and then only if \( rb' - (r-1)a' = rb - (r-1)a \). Hence the rows and columns of \( A(a, b) \) and \( A(a', b') \) are distinct provided that \( b' \neq b + \frac{a'}{a} (a' - a) \) for \( r = 1, 2, \ldots, p - 1 \). As \( r \) varies from 1 to \( p - 1 \), \( \frac{a'}{a} \) takes all values in \( \mathbb{Z}_p \), apart from the value 1. Hence in selecting \( b' \) it is necessary to avoid the \( p - 1 \) values \( b + \rho (a' - a) \) for \( \rho = 0, 2, 3, \ldots, p - 1 \) for each previous choice of \((a, b)\).

By arguing in a similar fashion regarding entries, we obtain exactly the same condition to avoid entry clashes between \( A(a, b) \) and \( A(a', b') \). It follows that at the \( c^{th} \) choice, there are at least \( p^{k-1} - (c-1)(p-1) \) choices for \( b' \) (rather more if there is multiple counting of excluded rows, columns and entries).

Now put \( C = \left\lfloor \frac{p^{k-1}}{p-1} \right\rfloor = \frac{p^{k-1} - 1}{p-1} \) and let \( c \leq C \) be a positive integer. Then it is possible to choose \( c \) subarrays of the form \( A(a, b) \) that are pairwise disjoint as regards rows, columns and entries. Suppose that the subarrays chosen are \( A(a_i, b_i) \) for \( i = 1, 2, \ldots, c \). Then the number of transversals in \( A_p^k \) that do not contain any of the triples \(((a_i, 0), (a_i, 0), (2a_i, 0))\) for \( i = 1, 2, \ldots, c \), and which can be constructed by trades on these arrays is at least

\[
(T^*)^c(p^{k-1})(p^{k-1} - (p - 1))(p^{k-1} - 2(p - 1)) \ldots (p^{k-1} - (c-1)(p-1)) > (T^*(p-1))^c \frac{C!}{(C-c)!}
\]

To see that these transversals are all distinct, consider any one of them, say \( T^* \). Each \( a_i \) for \( i = 1, 2, \ldots, c \) can be identified from those diagonal entries of \( A_i \) that do not form part of \( T^* \). Having identified an \( a_i \), there will be a triple of \( T^* \) of the form \(((a_i, 0), (rb_i - (r-1)a_i, r), (rb_i - (r-2)a_i, r))\) where \( r \neq 0 \). From this triple, \( r \) can be identified and hence also \( b_i \). Thus the subarrays \( A(a_i, b_i) \) can be recovered from \( T^* \), and the distinctness of the transversals follows. In fact any distinct choices of up to \( C \) values for \( a_i \) will yield distinct transversals. Hence we obtain the following theorem.

**Theorem 2.1** If \( p \) is an odd prime and \( k \) is a positive integer, then the number of transversals in the Latin square \( A_p^k \), denoted by \( T(A_p^k) \), satisfies the inequality

\[
T(A_p^k) > \sum_{c=0}^{C} \binom{p^{k-1}}{c} (T^*(p-1))^c \frac{C!}{(C-c)!}
\]
where \( C = \frac{p^{k-1}}{p-1} \) and \( T^* = T(A_p)(1 - \frac{1}{p}) \).

The final term in the summation (1) gives
\[
T(A_p^k) > \left( \frac{p^{k-1}}{C} \right) (T^*(p - 1))^C C!
= \frac{(p^{k-1}!)^C}{(p^{k-1} - C)!} (T^*(p - 1))^C
\]
Applying Stirling’s Theorem in the form \( r! = r^{r+\frac{1}{2}} e^{-r} \sqrt{2\pi} e^{o(1)} \) (as \( r \to \infty \)) to this expression for large \( k \) gives
\[
T(A_p^k) > [p^{k-1}T^*(p - 1)]^C \left[ \left( 1 - \frac{C}{p^{k-1}} \right)^{-(p^{k-1} - C + \frac{1}{2})} \right] \cdot e^{o(1)}. \tag{2}
\]

For \( p \geq 3 \) and \( k \geq 2 \) we have \( (1 - \frac{C}{p^{k-1}}) \leq (1 - \frac{1}{p}) \) and \( p^{k-1} - C + \frac{1}{2} > (p - 2)C \). Hence
\[
T(A_p^k) > \left[ p^k \left( \frac{p}{p - 1} \right)^{p-4} T(A_p)e^{-1} \right]^C \cdot e^{o(1)}.
\]
The square \( A_p^k \) has order \( n = p^k \) and \( C = \frac{n}{p(p-1)} - \frac{1}{p-1} \), so taking \( Q \) to be slightly less than \( \left( \frac{p}{p-1} \right)^{p-4} T(A_p)e^{-1} \) gives the following corollary.

**Corollary 2.1** If \( p \) is an odd prime, there exists \( Q > 0 \) such that for all sufficiently large \( k \),
\[
T(A_p^k) > (nQ)^{\frac{n}{p(p-1)}}.
\]

In fact if \( p \) is also sufficiently large, then using the result of [1], we may take \( Q = (3.246)^p \). However, the bound is clearly best when \( p \) is small. In the case \( p = 3 \), inequality (2) simplifies as follows. Firstly \( T(A_3) = 3 \), so \( T^* = 2 \). Also \( C = (3^{k-1} - 1)/2 \) and \( 3^{k-1} - C + \frac{1}{2} = 3^{k-1}/2 + 1 \). Hence
\[
T(A_3^k) > (4 \cdot 3^{k-1} \cdot e^{-1})^C \cdot \left( \frac{1}{2} + \frac{1}{3^{k-1}} \right)^{-(\frac{3^{k-1}}{2} + 1)} \cdot e^{o(1)}
= \left( \frac{4n}{3e} \right)^C \cdot 2^{C+\frac{1}{2}} \left( 1 + \frac{1}{3^{k-1}} \right)^{-(\frac{3^{k-1}}{2} + 1)} \cdot e^{o(1)}
= \left( \frac{8n}{3e} \right)^C \cdot 2^{\sqrt{2}} \cdot \frac{1}{\sqrt{e}} \cdot e^{o(1)},
\]
since \((1 + \frac{1}{r})^{-r} \to e^{-1}\) as \( r \to \infty \). Noting that \( 8/3e > 0.981 \) and that \( C = \frac{n}{6} - \frac{1}{4} \), we obtain
Corollary 2.2 For all sufficiently large $k$, $T(\mathcal{A}_3^k) > (0.981n)^{\frac{n}{3}}$, where $n = 3^k$.

Finally we remark that, by transitivity, the number of orthogonal mates of the Latin square $\mathcal{A}_p^k$ is $T(\mathcal{A}_p^k)/n$ (where $n = p^k$) and so Theorem 2.1 and its corollaries also provide lower bounds for this quantity.

References


