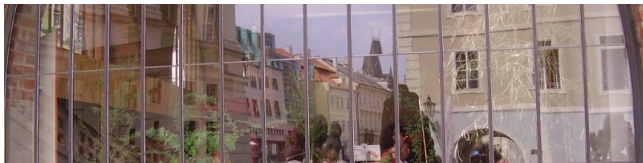


# Sylvester designs

Peter J. Cameron, University of St Andrews



Midsummer Combinatorics Workshop 2023

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I liked it so much that it is a bit surprising that I went on to group theory and combinatorics rather than topology and analysis.

## Two kinds of mathematics

In the preface, he says,

*It seems to me that a worthwhile distinction can be drawn between two types of pure mathematics. The first—which unfortunately is somewhat out of style at present—centers attention on particular functions and theorems which are rich in meaning and history, like the gamma function, or on juicy individual facts, like Euler’s wonderful formula*

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*The second is concerned primarily with form and structure.*

Most of us here, I think, are more comfortable with the second kind of mathematics. But today I will give you an example of the first.

## My topic

The topic is taken from the paper

- ▶ R. A. Bailey, P. J. Cameron, L. H. Soicher and E. R. Williams, Substitutes for the non-existent square lattice designs for 36 varieties, *J. Agricultural, Biological and Environmental Statistics* **25** (2020), 487–499.

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This paper may be the only appearance ever of the outer automorphism of the symmetric group  $S_6$  (my fact “rich in meaning and history”) in a journal of agricultural statistics. I will start with a little of the background.

## Block designs

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In this case, the way we allocate varieties to plots has an effect on the amount of information we can extract.



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The designs which achieve this are called **A-, D-, E-optimal** respectively.

## The concurrence graph

The associated parameters are determined by the Laplacian spectrum of a certain multigraph called the **concurrence graph**. The vertices of the graph are the varieties or treatments being tested; the number of edges between vertices  $v_i$  and  $v_j$  is the number of occurrences of  $v_i$  and  $v_j$  in the same block. (For example, a block containng three occurrences of  $v_i$  and two of  $v_j$  contributes 6 to this number.)

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The Laplacian matrix has  $(i, j)$  entry the negative of the number of edges from  $v_i$  to  $v_j$  if  $i \neq j$ , and the valency of  $v_i$  if  $i = j$ . It is positive semidefinite; the multiplicity of 0 is the number of connected components.



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I make one further assumption: the design should be **equireplicate**, that is, each treatment should be used the same number (say  $r$ ) of times.

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The *E*-optimal design maximizes the smallest non-trivial eigenvalue. This important parameter is connected with isoperimetric number and rate of convergence of a random walk.

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All these designs are optimal on all criteria, and are widely used in practice. They also have the good feature that, if one replicate is lost for some reason, the remaining  $r - 1$  replicates still carry an (optimal) square lattice design (provided that  $r > 2$ ).

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But what God takes away with one hand He gives with the other. For 6 is the only number  $k$ , finite or infinite, for which the symmetric group  $S_k$  of degree  $k$  has an outer automorphism. This can be used to construct good substitutes for the missing designs.

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I will briefly describe this “juicy individual fact”, using Sylvester’s quaint terminology.

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The symmetric group acts differently on  $A$  and  $X$ , giving rise to an outer automorphism.

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So there is a natural transformation from  $\Phi^2$  to the identity.



## Applications

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Related to the last is the construction of a graph which Norman Biggs called the **Sylvester graph**. Let  $X$  be the set of totals on  $A$ . The vertex set of the graph is  $A \times X$ ; there is an edge from  $(a, x)$  to  $(b, y)$  if and only if the duad  $\{a, b\}$  belongs to the syntheme  $x \cap y$ .

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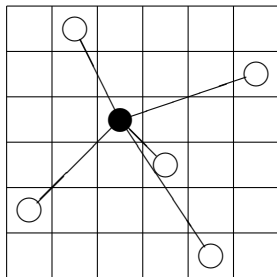
This is a distance-transitive graph of valency 5 on 36 vertices; its automorphism group is equal to the automorphism group of  $S_6$ , with order 1440. Its diameter is 3, and two vertices are at distance 3 if and only if they agree in one coordinate (same point of  $A$  or same total).

## Starfish

The Sylvester graph is drawn on a  $6 \times 6$  grid  $A \times X$ . A **starfish** is a closed vertex neighbourhood.

# Starfish

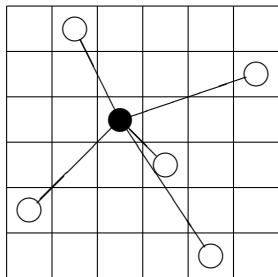
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A **galaxy** of starfish consists of all the starfish whose “heads” lie in a particular column. Our comment about distance 3 shows that the starfish in a galaxy are pairwise disjoint and so partition the set of vertices.

## The first Sylvester design

Now we can construct a block design by taking as blocks the rows and columns of the square grid together with the 36 starfish. It has 48 blocks of size 6, each point in 8 of them.

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All these designs do very well on the optimality criteria (especially  $A$ , the most commonly used in this context).

## Two more

Emlyn Williams maintains a program CycDesign, which uses methods including random search to find good block designs. After we announced the Sylvester design, he used his software to find another design with the same value on the A-criterion to four places of decimals. It turns out that it has exactly the same concurrence matrix, and so agrees on all criteria; but it is not the same design, since its automorphism group is trivial.

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# Two problems

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*Are Sylvester designs optimal (on the A, D and E criteria) among all designs with  $v = 36$ ,  $b = 48$ ,  $k = 6$  and  $r = 8$ ?*

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*Classify the Sylvester designs up to isomorphism.*

The second problem may be difficult. We do not know whether the three examples we know are the only ones, or whether there are billions of designs, or anywhere in between.