

There is No McLaughlin Geometry

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Abstract

We determine that there is no partial geometry \mathcal{G} with parameters $(s, t, \alpha) = (4, 27, 2)$. The existence of such a geometry has been a challenging open problem of interest to researchers for almost 40 years. The particular interest in \mathcal{G} is due to the fact that it would have the exceptional McLaughlin graph as its point graph. Our proof makes extensive use of symmetry and high-performance distributed computing, and details of our techniques and checks are provided. One outcome of our work is to show that a pseudogeometric strongly regular graph achieving equality in the Krein bound need not be the point graph of any partial geometry.

Keywords: partial geometry; pseudogeometric graph; McLaughlin geometry; McLaughlin graph; Krein bound; backtrack search.

MSC Codes: 51E14 (Primary); 05-04 (Secondary).

1 Introduction

For positive integers s, t, α , a *partial geometry* with *parameters* (s, t, α) , or a $\text{pg}(s, t, \alpha)$, is a point-line incidence structure such that

1. there are exactly $s + 1$ points on each line;
2. there are exactly $t + 1$ lines through each point;
3. every pair of distinct points are on at most one line (and so every pair of distinct lines meet in at most one point); and
4. for every line L and every point p not on L , there are exactly α lines through p meeting L .

Omitting the last condition, we obtain the definition of a *partial linear space* with *parameters* (s, t) , or a $\text{pls}(s, t)$.

Partial geometries, introduced by Bose [1], generalise certain important classes of finite geometries: generalised quadrangles, 2 - $(v, s + 1, 1)$ designs, nets, and the duals of these geometries. See [5] and [27] for useful surveys on partial geometries.

The *point graph* of a partial linear space \mathcal{P} has the points of \mathcal{P} as vertices and has $\{p, q\}$ as an edge if and only if the points p and q are distinct and on a common line of \mathcal{P} . It is well known (and first proved in [1]) that a $\text{pg}(s, t, \alpha)$ has a strongly regular point graph, with parameters

$$((s + 1)(st + \alpha)/\alpha, s(t + 1), s - 1 + t(\alpha - 1), (t + 1)\alpha). \quad (1)$$

A strongly regular graph with parameters of the form (1), with $s, t, \alpha \in \mathbb{Z}$, $1 \leq s, t$ and $1 \leq \alpha \leq \min\{s + 1, t + 1\}$, is called a *pseudogeometric* (s, t, α) -*graph*, and such a graph is called *geometric* if it is the point graph of at least one $\text{pg}(s, t, \alpha)$. It is known that if a pseudogeometric (s, t, α) -graph Δ is the point graph of a $\text{pls}(s, t)$, then this $\text{pls}(s, t)$ must be a $\text{pg}(s, t, \alpha)$ and Δ is geometric. This follows from the fact that if a pseudogeometric (s, t, α) -graph has an $(s + 1)$ -clique C , then every vertex not in C is adjacent to exactly α vertices in C (see [8, Lemma 1] and its proof).

It has long been an open problem of considerable interest whether there exists a partial geometry \mathcal{G} with parameters $(s, t, \alpha) = (4, 27, 2)$ (see [4, 5, 15, 17, 25]). Such a geometry would have 275 points and 1540 lines, and the point graph Γ of \mathcal{G} would be a strongly regular graph with parameters

$$(v, k, \lambda, \mu) = (275, 112, 30, 56).$$

Goethals and Seidel [7] showed that such a strongly regular graph is unique (up to isomorphism). Thus Γ would be the well-studied and fascinating McLaughlin graph, defined by J. McLaughlin [19] for the construction of his sporadic simple group, now called the McLaughlin group McL . The full automorphism group of Γ is $G \cong McL:2$, which acts transitively with permutation rank 3 on the set of vertices [19].

As in [25], we call a $\text{pg}(4, 27, 2)$ a *McLaughlin geometry*. The main purpose of this paper is finally to settle the existence of a McLaughlin geometry, unfortunately in the negative. We do this by proving that the McLaughlin graph is not the point graph of any $\text{pls}(4, 27)$.

The McLaughlin graph Γ is an example of a pseudogeometric (s, t, α) -graph achieving equality in the *Krein bound*

$$(s + 1 - 2\alpha)t \leq (s - 1)(s + 1 - \alpha)^2$$

(see [4, Theorem 7.6]). The problem of the existence of a McLaughlin geometry appears first to have been posed in [4], and was in connection with [4, Question 7.10] asking whether every pseudogeometric (s, t, α) -graph achieving equality in the Krein bound is geometric. It was proved in [4, Theorem 7.9] that this is indeed the case when $\alpha = 1$, so the McLaughlin graph was a particularly important test case. See also the Remark and Open Question in [5, p. 442]. The nonexistence of a McLaughlin geometry now shows that a pseudogeometric (s, t, α) -graph achieving equality in the Krein bound need not be geometric when $\alpha > 1$.

For brevity, throughout this paper we omit the term *putative* when writing about putative McLaughlin geometries and their substructures. For our proof, we fix a copy Γ of the McLaughlin graph. In the Appendix, we give explicit permutation generators for the automorphism group G of Γ , together with the construction of Γ from G . Although we focus on one specific pseudogeometric graph, the main ideas and techniques discussed are applicable more generally.

2 Candidate lines of a McLaughlin geometry

Given our copy Γ of the McLaughlin graph, the first step is to determine the candidates for lines of a McLaughlin geometry. Each candidate line is a 5-clique in Γ . There are exactly 15400 5-cliques in Γ , which can be readily obtained using Cliquer [20] or GRAPE [26] (see, for example, the Appendix). We denote the set of these 15400 cliques (or *candidate lines*, or simply *lines*) by \mathcal{C} .

We now give some basic properties of these cliques, which can also be easily checked computationally.

- Lemma 1.**
1. *Each vertex in Γ is in exactly 280 of the cliques in \mathcal{C} .*
 2. *Each edge in Γ is contained in exactly 10 of the cliques in \mathcal{C} .*
 3. *Each k -clique in Γ with $3 \leq k \leq 5$ is contained in exactly one of the cliques in \mathcal{C} .*
 4. *There are no k -cliques in Γ of size $k > 5$.*

Proof. The group G acts transitively on both the vertices and the edges of Γ . Consequently, each of the $275 \cdot 112/2 = 15400$ edges of Γ occur in $15400 \cdot 10/15400 = 10$ of the cliques in \mathcal{C} , and each of the 275 vertices of Γ occur in $15400 \cdot 5/275 = 280$ of the cliques in \mathcal{C} .

Since Γ is a pseudogeometric $(4, 27, 2)$ -graph, each vertex not in a given 5-clique is adjacent to exactly two vertices in that clique. It is shown in [15] that each 3-clique is contained in some 5-clique (or see the Appendix). This 5-clique C is unique, since otherwise there would be a vertex outside C that is adjacent to at least three vertices of C , which is not possible. This implies that also each 4-clique is contained in a unique 5-clique and that there can be no clique in Γ of size greater than 5. \square

The existence problem for a $\text{pg}(4, 27, 2)$ boils down to the problem of finding a subset of size 1540 of the set \mathcal{C} of 5-cliques such that each edge of the McLaughlin graph is in exactly one of the chosen 5-cliques. For this, the framework of exact cover [12, 13] could be considered, and indeed this approach is used in [17]. However, many further ideas are needed to solve the existence problem of a McLaughlin geometry, even with the large available computing resources. Indeed, it is clear from earlier studies [15, 17, 25] that constructing a McLaughlin geometry, or proving nonexistence, is a big challenge. As with other similar challenging problems [11], care has to be taken to find an efficient approach that utilizes the available symmetries.

3 The general approach

Our general strategy follows that described by Reichard [22]. This strategy was independently devised by the second author, and implemented in his GRAPE package [26] function `PartialLinearSpaces`, which can classify partial linear spaces, including partial geometries, with given parameters and point graph, up to isomorphism. In the present work, however, we needed

to employ new ideas and enhancements, implemented on a powerful 256-core computer cluster, to be able finally to solve the existence problem of a McLaughlin geometry.

We first define the concept of a bundle. If p is a point in a McLaughlin geometry, then the 28 lines through p meet pairwise only in p , for otherwise, there would be two distinct points on more than one line. Where p is a vertex in the McLaughlin graph Γ (we also call p a *point*), then a *bundle* through p is a set of 28 5-cliques whose pairwise intersection is $\{p\}$.

Our basic approach for an exhaustive search for a McLaughlin geometry is to consider the points $1, 2, \dots, 275$ of Γ , and given chosen bundles through $i - 1$ chosen points, p_1, \dots, p_{i-1} , to choose a new point p_i (which may depend on the points and bundles chosen so far), then consider all the possible bundles through p_i . Some bundles through p_i may be incompatible with previous choices, or may not be necessary to consider by symmetry or since they were eliminated from consideration in a previous case, but for each bundle through p_i that it is necessary to consider, we continue the search using a new point p_{i+1} not in $\{p_1, \dots, p_i\}$. The full search starts with $i = 1$.

3.1 Classifying bundles

Since the group G acts transitively on the points, the first point p_1 can be chosen arbitrarily, so we choose $p_1 = 1$, and start by classifying the bundles through this point, up to the action of the stabilizer U in G of p_1 . This stabilizer has shape $U_4(3).2$ [19] and order $|G|/275 = 2^8 \cdot 3^6 \cdot 5 \cdot 7 = 6531840$.

There are exactly 17729280 bundles through p_1 , forming just 36 U -orbits. This was already discovered by Pech and Reichard [21, Sect. 8.2], but no further details about the structures were given in that study.

We determined the 36 U -orbits of the 17729280 distinct bundles through p_1 using exact cover (`libexact` [12]): each 5-clique that contains p_1 covers the four other points on the candidate line, and we need to determine the sets (of size 28) of such 5-cliques that cover each the 112 vertices adjacent to p_1 exactly once. The Orbit–Stabilizer theorem was applied for validating the results; cf. [11, Sect. 10.2]. More precisely, it was checked that the number of bundles in each orbit determined during the search is $6531840/|A|$, where $|A|$ is the order of the stabilizer in U of an orbit representative.

We remark that the bundles through p_1 correspond to the “spreads” of the $\text{pg}(3, 9, 1)$ (or generalised quadrangle $\text{GQ}(3, 9)$), whose point graph is the induced subgraph Δ on the neighbors in Γ of p_1 , and that these spreads form just 26 orbits under the action of the automorphism group of Δ , of shape $U_4(3).D_8$ (see [2] and [21, Sect. 8.2]).

We use the 36 *lex-min* U -orbit representatives of the bundles in subsequent computations. This is an important detail, since, for example, references to specific points are not valid for arbitrary representatives. The natural order $1, 2, \dots, 275$ of the points naturally induces a lexicographic order on the candidate lines (which are sets of points), and so also on the sets of candidate lines. The *lex-min* U -orbit representatives of the bundles through p_1 were computed independently in two ways: one by a tailored C program and another using GRAPE [26]. The GRAPE computation made particular use of its included function `SmallestImageSet` [16], written by Steve Linton, which, given a permutation group $A \leq S_n$ and a subset S of $\{1, \dots, n\}$, determines the *lex-min* set in the A -orbit of S (without explicitly constructing this orbit).

To find the automorphism groups of graphs, we use *nauty* [18] in the current work. Isomorphism and automorphism problems for incidence structures encountered (such as sets of lines) are also conveniently handled by *nauty* after standard reductions. Furthermore, the `SmallestImageSet` function in GRAPE is very useful for testing isomorphism when isomorphism corresponds to two sets being in the same group orbit.

Note that, due to the transitivity of G on the points, our 36 *lex-min* U -orbit representatives form a set of representatives for the G -orbits of all the bundles through all the points. We consider two bundles to be *isomorphic* if they are in the same G -orbit. In the subsequent computations, it will be important to be able to distinguish between the 36 isomorphism classes of bundles with some invariant that can be computed reasonably quickly. Brouwer [2] describes the following invariant, which partitions the bundles into 11 classes.

Count the number of 4-sets F of lines in the bundle through p that satisfy the following property: there are four additional candidate lines through p that intersect each line in F in some point other than p . It follows that these four additional candidate lines must pairwise intersect only in p , for otherwise, we would have a triangle in the generalised quadrangle whose point graph is induced on the neighbors in Γ of p . Hence, with p removed, the eight lines consisting of a 4-subset F of the bundle together with four candidate lines meeting each element of F in a point form a 4×4 “grid”. The value of this invariant is between 0 and 63 for the 36 isomorphism classes.

We shall now consider a new invariant that is able to distinguish between all 36 isomorphism classes of bundles. Let p be a point and P be the set of points that are not adjacent in Γ to p . Given a bundle through p consider the set of candidate lines L that do not contain p but intersect two points of some line in the bundle through p . The number of such candidate lines is obviously $28 \cdot 6 \cdot 9 = 1512$. Each candidate line in L covers three pairs

of points in P . Moreover, each pair of points in P is covered by 0 to 10 candidate lines in L .

The values t_1, \dots, t_{10} , where t_i is the number of pairs of points in P covered exactly i times are now invariants. Clearly $\sum_{i=1}^{10} it_i = 1512 \cdot 3 = 4536$. The tuple $(t_1, t_2, \dots, t_{10})$ turns out to be an almost complete invariant — actually, it will suffice to use only a part of the tuple, for example, (t_1, t_2) — leaving only two pairs of isomorphism classes open.

To make the invariant complete one may further have a look at the candidate lines L' that intersect exactly two of the lines in the bundle in one point each. Let $L'' \subseteq L'$ be the subset of lines that do not intersect any of the sets in $\{C \cap P : C \in L\}$ in more than one point. Finally, find a line in the bundle that intersects the fewest number s of lines in L'' , and use s in the invariant.

The following invariants of the 36 isomorphism classes are listed in Table 1: the old invariant (Old), the values s, t_1, \dots, t_{10} for the new invariant, and the order $|\text{Stab}|$ of the stabilizer in G of a representative bundle.

Table 1 shows that six of the 36 representative bundles have $t_{10} > 0$. Hence, for each of these six bundles, there is an edge of Γ which does not occur in any feasible candidate line (as this edge is only covered by candidate lines which cannot be lines in a McLaughlin geometry containing that bundle). The fact that these six cases cannot lead to a McLaughlin geometry was discovered already by Reichard (as noted in [25, p. 252]), but the specific details were never published [23].

We remark that, given a bundle, a 113×1540 part of the 275×1540 point-line incidence matrix of a McLaughlin geometry \mathcal{G} is determined. We can see this making use of the fact that every point in Γ not on a given candidate line $C \in \mathcal{C}$ must be adjacent to exactly two points in C . This implies that if C_1 and C_2 are distinct candidate lines in our bundle with common point p , and $q \neq p$ is a point in C_1 , then q is adjacent to just one point other than p in C_2 , and this yields a total of $1512 = \binom{28}{2} 4$ edges to be covered once each by the lines of \mathcal{G} not in our bundle. Consequently, the points of the bundle induce a partial linear space having 28 lines of size 5 and 1512 lines of size 2.

3.2 Classifying pairs of bundles

Now, for each of the 30 lex-min representative bundles B through $p_1 = 1$ that have $t_{10} = 0$, we will choose a new point p_2 and determine all bundles through p_2 that are compatible with B , up to the action of the stabilizer of p_2 in the G -stabilizer of B . Two bundles are said to be *compatible* if no line of the first intersects any line of the second in exactly two points.

The order in which the points are completed, and in particular the choice

Table 1: Isomorphism classes of bundles

Nr	Old	s	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	Stab
1	0	64	1730	762	288	97	6	0	0	0	0	0	6
2	0	80	1603	840	336	35	21	0	0	0	0	0	7
3	0	80	1568	910	266	70	14	0	0	0	0	0	14
4	0	84	1568	910	266	70	14	0	0	0	0	0	14
5	0	68	1673	875	231	70	28	0	0	0	0	0	14
6	0	76	1736	770	301	70	7	7	0	0	0	0	14
7	0	70	1686	981	117	93	18	9	3	0	0	0	18
8	0	78	1626	837	360	15	0	9	6	0	0	0	18
9	0	54	1800	810	207	108	0	0	9	0	0	0	18
10	0	64	1640	873	270	60	18	0	0	0	0	1	18
11	0	82	1589	903	231	112	0	0	0	0	0	0	21
12	0	84	1589	903	231	112	0	0	0	0	0	0	21
13	1	66	1728	852	208	102	0	12	0	0	0	0	16
14	1	50	1624	994	184	32	32	14	0	0	0	0	16
15	1	73	1792	752	272	92	0	8	0	1	0	0	16
16	1	52	1824	739	264	92	8	4	0	0	0	1	16
17	1	73	1824	840	216	30	24	24	0	0	0	0	48
18	1	27	1896	780	168	120	0	12	0	3	0	0	48
19	2	70	1708	832	264	57	26	0	2	0	0	0	2
20	3	73	1648	855	285	51	21	0	2	0	0	0	3
21	3	59	1700	870	240	64	12	6	0	3	0	0	24
22	3	50	1764	831	240	62	12	12	0	0	0	1	24
23	4	60	1773	726	315	72	12	3	0	0	0	0	6
24	6	60	1717	789	309	47	18	6	0	0	0	0	6
25	7	82	1520	1008	232	52	8	4	0	4	0	0	16
26	7	68	1664	876	272	40	16	8	0	2	0	0	32
27	7	60	1664	994	144	80	16	0	0	4	0	2	32
28	7	89	1368	1080	264	36	0	12	0	0	0	0	48
29	9	0	1584	1242	0	36	0	54	0	0	0	0	432
30	9	38	1968	837	0	216	0	0	0	0	0	3	432
31	15	64	1728	808	280	60	8	12	0	0	0	0	16
32	15	48	1704	792	312	60	0	12	0	0	0	0	48
33	15	78	1664	908	224	76	0	8	0	4	0	0	64
34	15	72	1792	948	96	112	0	12	0	0	0	4	192
35	31	64	1824	792	192	120	0	12	0	0	0	0	192
36	63	0	2016	756	0	252	0	0	0	0	0	0	12096

of p_2 for each chosen bundle through p_1 , are crucial. We shall now have a closer look at the cases when p_1 and p_2 are adjacent and nonadjacent.

When p_1 and p_2 are adjacent, their completion has a line $\ell = \{p_1, p_2, a, b, c\}$. Given the bundle through p_1 , out of the 280 candidate lines through p_2 , the infeasible lines through p_2 are exactly those lines that contain p_1 and one other point of ℓ . This gives a total of $280 - (1 + 4 \cdot 9) = 243$ feasible lines.

One may also see that the bundle through p_1 reduces the number of possible bundles through p_2 from 17729280 to 1772928, that is, by a factor of exactly 10. This follows from the fact that given p_1 , out of the ten possibilities for the line through p_1 and p_2 , one has been fixed. Since the G -stabilizer of p_2 is transitive on the set of 5-cliques containing that point, and the bundle through p_1 does not restrict any candidate lines through p_2 that intersect ℓ only in that point, the reduction factor is indeed 10.

If p_1 and p_2 are nonadjacent, then the vertices in Γ adjacent to both points induce the Gewirtz graph, which is the unique strongly regular graph with parameters $(56, 10, 0, 2)$ (see [3]). Every candidate line through either p_1 or p_2 intersects the vertex set of that graph in exactly 2 vertices, and a bundle partitions it into 28 pairs. Consequently, given a bundle through p_1 , there are $280 - 28 = 252$ feasible lines for a bundle through p_2 . (Recall that a 3-clique is in a unique candidate line by Lemma 1.)

Although the number of feasible lines through p_2 is smaller when p_1 and p_2 are adjacent than when they are nonadjacent, it turns out that the number of compatible bundles is smaller in practice when they are nonadjacent. We do not have a formal argument for this, but the following probabilistic approach gives a result surprisingly close to experimental results.

Each bundle through either of the nonadjacent points p_1 and p_2 covers 28 edges out of the 280 edges in the Gewirtz graph. The probability that two sets of 28 randomly chosen edges are distinct is

$$\frac{\binom{252}{28}}{\binom{280}{28}} \approx 0.04454.$$

This value is smaller than $1/10 = 0.1$. Although this reasoning cannot be directly applied to the case of more than two completed points, practical experiments show that independent sets are indeed a proper choice when extending larger set of points.

When choosing the second point p_2 to complete amongst those vertices (other than p_1) that are not adjacent to p_1 , the possible choices correspond to the orbits of these points under the stabilizer in G of the given bundle B through p_1 . Isomorph rejection will be carried out on the compatible bundles through the chosen p_2 , using the action of the stabilizer K of p_2 in

the G -stabilizer of B .

Let $|\text{Stab}|$ be the order of the stabilizer in G of the bundle B through $p_1 = 1$, and let l be the length of that group's point-orbit containing p_2 . Then the group K above will have order $|\text{Stab}|/l$. Let N be the number of bundles through p_2 that are compatible with the first bundle B . It turns out that most sets of two bundles have only trivial symmetries, so the number of solutions up to symmetry is approximately $N_1 := Nl/|\text{Stab}|$. The point p_2 is chosen so that N_1 is minimized. The exact number of solutions up to symmetry is denoted by N_2 . The Orbit–Stabilizer theorem is used also here to validate the results. For each of the 30 lex-min isomorphism class representative bundles through p_1 which were not rejected in the first step, the compatible bundles through the chosen p_2 were classified and their lex-min K -orbit representatives were computed. This was done independently in two ways: one by a tailored C program (calling *nauty* and *libexact*) and another using *GRAPE* (and its function `SmallestImageSet`).

In Table 2 we now list information about each case and chosen point p_2 , ignoring the six cases that were rejected in the first step. The notation given above is used for the columns of the table. The last two columns, N_3 and H , will be discussed in the next subsection.

3.3 Completing the search

We have already seen that six types of bundles need not be considered at all in the computer search, splitting the overall search into 30 cases, with one case for each of the remaining bundle types, where we shall be searching for a McLaughlin geometry containing a bundle of that type. It is clear that after a case for a given bundle type is completed, that bundle type may be *cancelled*, that is, eliminated from consideration in the cases of the search to follow. A bundle of a cancelled type can be recognised via our bundle isomorphism class invariant. The order in which the cases are considered will have an impact on the overall running time.

The value of N_2 in Table 2 gives a rough estimate of the time it takes to complete the cases (ignoring possible cancelled cases). It further turns out that the impact of a cancelled bundle type on the subsequent cases is roughly inversely proportional to $|\text{Stab}|$. Consequently, a reasonable heuristic for ordering the parts is via the value $H := N_2|\text{Stab}|$; this value is given in the last column of Table 2. (Earlier approaches of using invariants and splitting up the search into many parts are, for example, [9, 10].)

We define an order for the parts based on H , but put case 36 early since that is a very small case and good for testing. The order is as follows

Table 2: Choices for second point

Nr	Stab	p_2	N	l	N_1	N_2	N_3	H
1	6	68	940320	1	156720	157760	72811	946560
2	7	161	750620	1	107231	107246	74493	750722
3	14	16	1072194	1	76585	77641	25505	1086974
4	14	79	1055464	1	75390	76474	26850	1070636
5	14	87	1041676	1	74405	75034	27941	1050476
6	14	159	1078178	1	77013	78153	23269	1094142
7	18	136	1159506	1	64417	65666	17619	1181988
8	18	69	1032450	3	172075	172266	10186	3100788
9	18	56	1089000	3	181500	181742	7044	3271356
10								
11	21	27	1356738	1	64607	64610	15233	1356810
12	21	79	1356738	1	64607	64610	14147	1356810
13	16	106	431840	1	26990	27412	25365	438592
14	16	172	583384	1	36461	37204	33452	595264
15	16	118	504528	2	63066	63066	24992	1009056
16								
17	48	18	851600	6	106450	106450	846	5109600
18	48	126	565584	3	35349	35578	6749	1707744
19	2	220	894832	1	447416	448417	288705	896834
20	3	180	600438	1	200146	200146	176116	600438
21	24	190	1209360	1	50390	50718	12620	1217232
22								
23	6	68	776563	3	388282	388842	52122	2333052
24	6	240	714792	1	119132	120096	90940	720576
25	16	16	1053336	2	131667	132016	20285	2112256
26	32	3	402504	4	50313	50313	10310	1610016
27								
28	48	37	571676	6	71459	71683	1348	3440784
29	432	8	1048560	36	87380	87778	67	37920096
30								
31	16	42	457198	4	114300	114670	20561	1834720
32	48	16	485100	6	60637	60746	4104	2915808
33	64	73	1216976	2	38030	38207	2705	2445248
34								
35	192	38	402712	12	25169	25441	250	4884672
36	12096	8	396552	36	1180	1231	1160	14890176

(including the six cases that need not be considered at all at this stage):

10 → 16 → 22 → 27 → 30 → 34 → 36 → 13 → 14 → 20 → 24 → 2 →
 19 → 1 → 15 → 5 → 4 → 3 → 6 → 7 → 21 → 11 → 12 → 26 →
 18 → 31 → 25 → 23 → 33 → 32 → 8 → 9 → 28 → 35 → 17 → 29

Having decided the order, the structures enumerated under N_2 in Table 2 can immediately be reduced by removing the bundles whose types will be cancelled before a given case is handled. The numbers of remaining structures, which are seeds for the final stage, are given in column N_3 of the same table.

The idea of considering independent sets of points to complete turned out to have further benefits when programming the search. For various reasons related to speed and memory requirement, we want to predetermine a set of points to consider in the search. Here we obviously rely on the assumption that it suffices to consider a relatively small set of points to prove nonexistence. Results by Reichard [22, Sect. 5.3] give an indication that this is indeed the case.

There are many independent sets in Γ , so the choice of points is not obvious. We use the following approach. We first find the set S of points other than p_1 and p_2 that are neither adjacent to p_1 nor to p_2 . From the parameters of Γ , we know that $|S| = 105$. Let $B(p)$ be the number of bundles through p that are compatible with both of the two bundles through p_1 and p_2 . For a given n , we now find an independent set $I \subseteq S$, $|I| = n$ that minimizes $\sum_{p \in I} B(p)$. We use $n = 9$. (Since all pairs of nonadjacent vertices are in one orbit of the automorphism group of Γ , the number of independent sets I of a given size to consider will not depend on the partial solution; for $n = 9$, it is 18579960.) To get an upper bound on the size of the data structures needed, one may further require that $\max_{p \in I} B(p) < u$, for some constant u , when minimizing $\sum_{p \in I} B(p)$. We here use this additional condition with $u = 10^5$.

The core of the search is basic backtrack search. Throughout the search, the candidate bundles through each of the considered points are maintained. On each level of the search, the point to consider is first determined. Specifically, a point with the fewest candidates is chosen. All candidate bundles for that point are then considered in order. For each fixed bundle, the candidate sets for the other points are reduced and the procedure described here is recursively repeated.

The core task of the backtrack search is to determine whether two bundles are compatible. At one extreme, one could preprocess every pair of candidate bundles and tabulate one bit for the result (this is essentially about determining the edges of a graph in which a clique search is to be carried out).

However, with, say, 300000 candidates in total, the task of determining a matrix with $(3 \cdot 10^5)^2 = 9 \cdot 10^{10}$ entries is time-consuming and, in particular, a substantial amount of memory is required.

At the other extreme, one may process each pair of bundles as they appear in the search. This requires that up to $28 \cdot 28 = 784$ pairs of lines be compared, which is a rather large constant. Actually, this approach was taken when carrying out a partial check of the results with an independent program. Between these extremes, there are several other possibilities, out of which the following was chosen.

Assume that we compare a bundle through point p with a bundle through a nonadjacent point p' . Now consider the set P of points that will lie on lines through p as well as lines through p' . The size of P equals the parameter $\mu = 56$ for Γ . We have seen earlier that P induces in Γ a strongly regular graph with parameters $(56, 10, 0, 2)$, the Gewirtz graph, which has $56 \cdot 10/2 = 280$ edges. Each bundle through either p or p' covers exactly 28 of the 280 edges. We now have the information needed for the data structure.

Let I be the (independent) set of points to be completed in the search. For each pair (B, p) , where B is a candidate bundle through p' , such that $p', p \in I$ and $p' \neq p$, determine and save a 280-bit vector with 28 1s indicating which pairs of points of lines in B are in the common neighborhood of p' and p . When comparing two bundles, it now suffices to compare two 280-bit vectors. This can be implemented by checking whether five AND operations on 64-bit integers all produce 0. This very fast method of determining compatibility of bundles was crucial to the success of our search.

4 Results

The backtrack search described in Section 3.3 was implemented in C and executed on a 256-core cluster with 2.4-GHz Intel Xeon E5-2665 processors. As the $n = 9$ points could not be completed in any of the cases, we have the following result.

Theorem 1. *There is no partial geometry with parameters $(s, t, \alpha) = (4, 27, 2)$, that is, there is no McLaughlin geometry.*

For the 30 cases, we collect the main data in Table 3. We give the total run time (in core-days), run time per instance of the case (the number of instances is N_3 in Table 2), and the maximum number of points completed in the search. The total hardware run-time was approximately 250 core-years, but since in some parts of the search virtual cores were used, the times per case given in Table 3 sum to rather more than this.

The length of our computer search was at the borderline of what was doable with the resources available to the authors. Consequently, a lot of effort was put into both the general approach and the specific details described in this paper. In retrospect, the authors feel that more effort should still have been put on one part, namely on deciding the order in which the bundle types are handled. The order used, displayed in the beginning of Section 3.3, was obtained with a heuristic, but additional computational experiments might have led to a different order and faster computations.

Correctness is one of the major issues of computer searches [14, 24]. There are effective validation methods whenever the solution set for an instance of a classification problem is nonempty [11, Sect. 10.2], which can be applied to the initial phases of this search as we have seen. However, for the final phase, which produces no solutions, the situation is different. Also notice that the idea of considering subcases to avoid redundant computations, which was crucial for the success of the work, means that the following argument *cannot* be used: if something exists, then it can be found in many ways.

Two measures were taken to minimize the probability of error. A computing cluster with error-correcting code (ECC) memory was used to minimize the probability of hardware error. Moreover, the results of a different, basic (and therefore slow) implementation of the final backtrack search were compared with the main implementation for a part of the search tree (comparing very specific details).

Having answered the existence question of a McLaughlin geometry in the negative, one may continue and ask for the largest number of 5-cliques (candidate lines) in the McLaughlin graph such that no two distinct such cliques intersect in two points. Mathon [17] found such packings of size 1120, on which one could try to improve. Finding the exact answer for this problem does not seem to be within reach.

Appendix

In this Appendix we present a GAP/GRAPE logfile specifying the construction of our standard fixed copy of the McLaughlin graph Γ , used in all our computations. The group G , obtained from the GAP library of primitive groups and given here by explicit generators, is our standard copy of the automorphism group of Γ . The vertex-set of Γ is $\{1, \dots, 275\}$, and the edge-set is the G -orbit of $\{1, 2\}$.

Checks are included showing G to have the right order, Γ to be a strongly regular graph with the correct parameters, $G = \text{Aut}(\Gamma)$, and that the maximal cliques of Γ (maximal with respect to containment) are precisely the

Table 3: Search data

Nr	Time (d)	Time/Instance (min)	Max. level
1	2325	46.0	6
2	13958	269.8	7
3	217	12.3	6
4	264	14.2	6
5	301	15.5	6
6	162	10.0	6
7	100	8.2	6
8	45	6.4	5
9	30	6.2	4
10			
11	88	8.3	6
12	76	7.8	5
13	6942	394.1	7
14	6619	284.9	7
15	302	17.4	6
16			
17	4	6.4	3
18	34	7.3	5
19	42822	213.6	7
20	78792	644.2	8
21	67	7.7	6
22			
23	271	7.5	5
24	15988	253.2	7
25	86	6.1	5
26	50	7.0	6
27			
28	6	6.3	4
29	1	5.9	2
30			
31	96	6.7	5
32	18	6.2	5
33	10	5.5	5
34			
35	1	5.8	3
36	66	82.3	6

cliques of size 5, of which there is a single G -orbit, which has size 15400.

```
gap> LoadPackage("grape");
-----
Loading GRAPE 4.6.1 (Graph Algorithms using PERmutation groups)
by Leonard H. Soicher (http://www.maths.qmul.ac.uk/~leonard/).
Homepage: http://www.maths.qmul.ac.uk/~leonard/grape/
-----
true
gap> G:=Group( [
> ( 1, 2)( 3, 4)( 5, 7)( 6, 8)( 9, 12)( 10, 13)( 11, 15)( 14, 19)
> ( 16, 21)( 17, 22)( 18, 24)( 20, 27)( 23, 31)( 25, 33)( 26, 34)( 28, 37)
> ( 29, 38)( 30, 40)( 32, 43)( 35, 47)( 36, 48)( 39, 51)( 41, 53)( 42, 54)
> ( 44, 57)( 45, 58)( 46, 60)( 49, 63)( 50, 64)( 52, 67)( 55, 71)( 56, 72)
> ( 59, 76)( 61, 78)( 62, 79)( 66, 82)( 68, 85)( 69, 86)( 70, 88)( 73, 92)
> ( 75, 94)( 77, 97)( 80,101)( 81,102)( 83,105)( 84,106)( 87,110)( 89,112)
> ( 90,113)( 91,115)( 93,118)( 95,120)( 96,121)( 98,123)( 99,109)(100,125)
> (103,129)(104,130)(107,133)(108,134)(111,137)(114,140)(116,142)(117,128)
> (119,144)(122,147)(124,149)(126,139)(131,153)(132,154)(135,158)(136,159)
> (138,161)(141,164)(143,167)(145,170)(146,172)(148,175)(150,177)(151,178)
> (152,179)(157,183)(160,187)(162,189)(163,190)(165,168)(166,193)(169,195)
> (171,196)(174,197)(176,192)(180,204)(181,201)(182,206)(188,209)(191,213)
> (194,216)(198,221)(199,222)(200,208)(202,225)(203,227)(205,230)(207,232)
> (210,218)(211,233)(212,235)(215,236)(217,238)(219,240)(220,241)(223,244)
> (224,245)(226,247)(228,249)(229,250)(231,252)(234,255)(237,257)(239,242)
> (243,259)(246,261)(248,264)(253,267)(254,268)(256,269)(258,266)(260,270)
> (262,271)(263,265)(272,274)(273,275),
> ( 1, 3, 5)( 4, 6, 9)( 7, 10, 14)( 8, 11, 16)( 12, 17, 23)
> ( 13, 18, 25)( 15, 20, 28)( 19, 26, 35)( 21, 29, 39)( 22, 30, 41)
> ( 24, 32, 44)( 27, 36, 49)( 31, 42, 55)( 33, 45, 59)( 34, 46, 61)
> ( 38, 50, 65)( 40, 52, 68)( 43, 56, 73)( 48, 62, 80)( 51, 66, 83)
> ( 53, 69, 87)( 54, 70, 89)( 57, 74, 93)( 58, 75, 95)( 60, 77, 98)
> ( 63, 81,103)( 64, 76, 96)( 67, 84,107)( 71, 90,114)( 72, 91,116)
> ( 78, 99,124)( 79,100,126)( 82,104,131)( 85,108,112)( 86,109,135)
> ( 88,111,138)( 92,117,123)( 94,119,125)( 97,122,148)(101,127,150)
> (102,128,151)(106,132,155)(110,136,160)(113,139,162)(115,141,165)
> (118,143,168)(120,145,171)(121,146,173)(129,144,169)(130,152,180)
> (133,156,182)(134,157,184)(140,163,191)(142,166,172)(147,174,198)
> (149,176,200)(153,181,205)(158,185,207)(159,186,170)(161,188,210)
> (164,192,214)(167,194,217)(175,199,223)(177,201,224)(178,202,226)
> (179,203,228)(183,193,215)(187,208,209)(189,211,234)(190,212,221)
> (195,218,239)(196,219,233)(197,220,242)(204,229,251)(206,231,253)
> (216,237,255)(222,243,260)(225,246,262)(227,248,257)(230,238,258)
> (232,254,269)(235,256,267)(240,249,265)(247,263,261)(250,264,268)
> (252,266,272)(270,271,273) ]);
gap> gamma:=EdgeOrbitsGraph(G,[1,2]);
gap> # Now gamma is our standard copy of the McLaughlin graph,
gap> # with gamma.group set to G. We do some checks:
gap> Size(G);
```



```

1796256000
gap> GlobalParameters(gamma);
[ [ 0, 0, 112 ], [ 1, 30, 81 ], [ 56, 56, 0 ] ]
gap> G=AutomorphismGroup(gamma);
true
gap> G=gamma.group;
true
gap> # We now determine the maximal cliques of gamma, and that these
gap> # are precisely the cliques of size 5, of which there is a single
gap> # G-orbit, which has size 15400.
gap> K:=CompleteSubgraphs(gamma,-1,2);
[ [ 1, 2, 17, 45, 193 ] ]
gap> # Now K is a set of G-orbit representatives of the maximal
gap> # cliques of gamma.
gap> cliques:=Set(Orbit(G,K[1],OnSets));;
gap> Length(cliques);
15400

```

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