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Diamond-free degree sequences

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Abstract. While attempting to classify partial linear spaces produced during the execution of an extension of Stinson's hill-climbing algorithm a new problem arises, that of generating all graphical degree sequences that are diamond-free (i.e. have no diamond as subgraph) and satisfy additional constraints. We formalize this new problem, propose a constraint programming solution and list all satisfying degree sequences of length 8 to 16 inclusive.

1 Introduction

We introduce a new problem, CSPLib number 50 [1], to generate all degree sequences that have a corresponding diamond-free graph with secondary properties. This arises naturally from a problem in mathematics to do with partial linear spaces; we devote Section 2 to this. The motivation described in Section 3 is the challenge of the necessary computational effort arising from the large number of symmetries within the models (see Section 4). We introduce two constraint programming models. The second model is an improvement on the first, and this improvement largely consists of breaking the problem into three stages: the first stage produces degree sequences that satisfy arithmetic constraints, the second stage tests that a given degree sequence is graphical and if it is the third stage determines if there exists a graph with that degree sequence that is diamond-free. We now present the problem in detail and give

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motivation for it. In Section 4 two models, in Section 5 a list of solutions are presented. Finally in Section 6 we conclude and suggest future work.

2 Problem definition

Given a simple undirected graph $G = (V, E)$, V is the set of vertices and E the set of undirected edges. The edge $\{u, v\} \in E$ if and only if vertex u is adjacent to vertex v in G. The graph is simple in that there are no loop edges, i.e. $\forall_{v \in V}$ $[\{v, v\} \notin E]$. Each vertex v in V has a degree $\delta(v) = |\{\{v, w\} : \{v, w\} \in E\}|$, i.e. the number of edges incident on that vertex. A diamond is a set of four vertices in V such that there are five edges between those vertices (see the diamond in Figure 1).

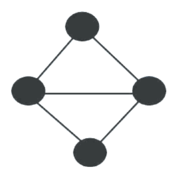

Figure 1: The diamond graph (four vertices and five edges)

Conversely, a graph is diamond-free if it has no diamond as a subgraph, i.e. for every set of four vertices the number of edges between those vertices is at most four. Determining whether a graph is diamond-free is a polynomial-time problem. E.g. checking every four vertices for a diamond is at worst case $\Theta(n^4)$. Note that a diamond is sometimes referred to as a $K_4 - e$ graph. Our definition of a diamond-free graph agrees with that of [14] which addresses a different, but related problem. That is, identifying degree sequences for which there is a realisation containing a diamond as a subgraph. Others [6, 7] use the term diamond-free to denote a graph which has no diamond as an *induced* subgraph (in which case a K_4 is an allowable subgraph, unlike in our case). A further definition of a diamond-free graph [2] is a graph G with no diamond as a *minor*, i.e. a graph (isomorphic to one that can be) obtained from a subgraph of G by zero or more edge contractions.

In our problem we have additional properties required of the degree sequences of the graphs, in particular that the degree of each vertex is greater than zero (i.e. isolated vertices are disallowed), the degree of each vertex is divisible by 3 and the sum of the degrees is divisible by 12 (i.e. $|E|$ is divisible by 6).

The problem is then for a given value of n, such that $|V| = n$, produce all degree sequences $\delta(1) \geq \delta(2) \geq ... \geq \delta(n)$ such that there exists a diamond-free graph with that degree sequence, each degree is non-zero and divisible by 3, and the number of edges is divisible by 6. In Figure 2 we give as an example the unique degree sequence for $n = 8$ that satisfies our arithmetic constraints, a corresponding diamond-free graph and its adjacency matrix.

```
3 3 3 3 3 3 3 3

0 0 0 0 0 1 1 1
0 0 0 0 0 1 1 1
0 0 0 1 1 0 0 1
0 0 1 0 1 0 1 0
0 0 1 1 0 1 0 0
1 1 0 0 1 0 0 0
1 1 0 1 0 0 0 0
1 1 1 0 0 0 0 0
```

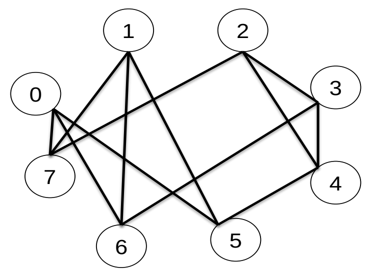

Figure 2: Unique degree sequence for $n = 8$ with a corresponding diamond-free graph and its adjacency matrix

3 Motivation

The problem is a byproduct of attempting to classify partial linear spaces that can be produced during the execution of an extension of Stinson's hill-climbing algorithm [3, 4, 5, 15] for block designs with block size 4. First we need some definitions.

Definition 1 *A Balanced Incomplete Block Design (BIBD) is a pair* (V, B) *where* V *is a set of* n *points and* B *a collection of subsets of* V *(blocks) such that each element of* V *is contained in exactly* r *blocks and every* 2*-subset of* V *is contained in exactly* λ *blocks.*

Variations on BIBDs include *Pairwise Balanced Designs* (PBDs) in which blocks can have different sizes, and *linear spaces* which are PBDs in which every block has size at least 2. It is usual to refer to the blocks of a linear space as a *line*. A partial linear space is a set of lines in which every pair appears in *at most* λ blocks. Here we refer to a BIBD with $\lambda = 1$ as a *block design* and to a partial linear space with $\lambda = 1$, having s_i lines of size i, where

$i \geq 3$ and $s_i > 0$ as a $3^{s_3}4^{s_4}\ldots$ structure. For example, a block design on 7 points with block size 3 is given by the following set of blocks:

$$\{(1,2,3),(1,6,7),(1,4,5),(2,5,6),(3,4,6),(3,5,7),(2,4,7)\}$$

and a $3^4 4^1$ structure on 8 points by the following set

$$\{(1,2,3,4),(1,5,6),(1,7,8),(2,5,7),(2,6,8)\}$$

Note that in the latter case we do not list the lines of size 2. Block designs with block size 3 are known as Steiner Triple Systems (STSs). These exist for all n for which $n \equiv 1,3 \pmod 6$ [12]. For example the block design given above is the unique STS of order 7 (STS(7)). Similarly block designs with block size 4 always exist whenever $n \equiv 1,4 \pmod{12}$.

```
STINSON(n)
LivePairs ← {(i,j) : 1 ≤ i < j ≤ n}
Blocks ← ∅
while LivePairs ≠ ∅
        choose pairs (x,y) and (y,z) from LivePairs
        LivePairs ← LivePairs \ {(x,y)}
        LivePairs ← LivePairs \ {(y,z)}
        if (x,z) ∈ LivePairs
              LivePairs ← LivePairs \ {(x,z)}
        else Blocks ← Blocks \ {(w,x,z) : (w,x,z) ∈ Blocks}
              LivePairs ← LivePairs ∪ {(w,x)}
              LivePairs ← LivePairs ∪ {(w,z)}
        Blocks ← Blocks ∪ {(x,y,z)}
return Blocks
```

Algorithm STINSON above allows us to generate an STS for any n and is due to Stinson [13]. This algorithm always works, i.e. it never fails to terminate due to reaching a point where the STS is not created and there are no suitable pairs (x,y) and (y,z).

A natural extension to this algorithm, for the case where block size is 4, is proposed in algorithm STINSON4. Note that the triples in set $WeightedTriples$ are all initially assigned weight 0 in line 1. Triples can only be selected to make a new block if they have weight zero. If S is a set of triples and X a set of points then the algorithms INCREASEWEIGHT(X,S) and DECREASEWEIGHT(X,S) (lines 6 and 9) increment (decrement) the weight of every element of S that contains π, for all pairs π of distinct points from X.

```
STINSON4(n)
WeightedTriples ← {⟨(i, j, k), 0⟩ : 1 ≤ i < j < k ≤ n}
Blocks ← ∅
while ⟨(w, x, y), 0⟩ ∈ WeightedTriples ∧ ⟨(x, y, z), 0⟩ ∈ WeightedTriples
        choose ⟨(w, x, y), 0⟩ and ⟨(x, y, z), 0⟩ from WeightedTriples
        for (u, v, w, z) ∈ Blocks
            DECREASEWEIGHT({u, v, w, z}, WeightedTriples)
            Blocks ← Blocks \ {(u, w, x, z)}
        Blocks ← Blocks ∪ {(w, x, y, z)}
        INCREASEWEIGHT({w, x, y, z}, WeightedTriples)
return Blocks
```

Algorithm STINSON4 does not always work. It is possible for a situation to be reached from which one pair of triples is constantly swapped with another, in which case the algorithm fails to terminate. It is also possible for the algorithm to terminate but fail to create a block design due to reaching a point at which *WeightedTriples* contains elements of weight zero but does not contain suitable triples (w, x, y) and (x, y, z) with weight zero. In this case the algorithm produces a 4^{s_4} structure (where s_4 is less than the number of blocks in the corresponding block design) for which the complement has no pair of triples (w, x, y), (x, y, z), with weight zero. I.e. the complement graph is diamond-free. When $n = 13$ the algorithm either produces a block design or a 4^8 structure whose complement graph consists of 4 non-intersecting triangles.

The next open problem therefore is for $n = 16$. If the algorithm terminates but does not produce a block design, what is the nature of the structure it does produce? To do this, we need to classify the 4^{r_4} structures whose complement graph is diamond-free.

The cases for which the 4^{s_4} structure has at least 2 points that are in the maximum number of blocks (5) are fairly straightforward. (There are fewer cases as this number increases.). However if the number of such points is 0 or 1, there is a large number of sub-cases to consider. The problem is simplified if we can dismiss potential 4^{s_4} structures because the degree sequences of their complements can not be associated with a diamond-free graph. This leads us to the problem outlined in this report: to classify the degree sequences of diamond-free graphs of order 15 and 16. Note that each point that is not in 5 blocks is either in no blocks or is in blocks with some number of points, where that number is divisible by 3. Thus for every point there is a vertex in the complement graph whose degree is also divisible by 3. In addition, since the number of pairs in both a block design on 16 points and a 4^{s_4} structure are divisible by 6, the number of edges in the complement graph must be divisible by 6. We can immediately eliminate some cases via the following lemmas. In all cases G is a diamond-free graph with n vertices for which every vertex has degree greater than 0 and divisible by 3.

Lemma 2 *If* $n = 16$ *then no vertex has degree* 15.

Proof. Suppose that u be a vertex that has degree 15. Then all other vertices are adjacent to u. Let v be such a vertex. Since v has degree at least 3, there are two vertices, w and x that are adjacent to both u and v. There is a diamond on vertices u, v, w and x. This is a contradiction. □

Lemma 3 *If* $n = 15$ *and* $\delta(1) = 12$ *then the degree sequence is either*

1. $(12, 12, 12, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$, *or*
2. $(12, 6, 6, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$.

Proof. Let u be a vertex that has degree 12 and $N(u)$ the set of vertices that are in the neighbourhood of (i.e. adjacent to) u. Then there are two vertices, v and w that are not u and are not in $N(u)$. No element of $N(u)$ can have degree greater than 3, for then it would have degree at least 6 and must be adjacent to at least two other elements of $N(u)$, and we would have a diamond. Let $\delta(v)$ and $\delta(w)$ be the degrees of v and v respectively. Without loss of generality we can assume that $\delta(v) \geq \delta(w)$. Then G has degree sequence $(12, \delta(v), \delta(w), 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$, where $\delta(v) + \delta(w)$ is divisible by 12. Hence $(\delta(v), \delta(w))$ is $(12, 12)$, $(9, 3)$ or $(6, 6)$.

If $(\delta(v), \delta(w)) = (12, 12)$ there is a solution. In this case every element of $N(u)$ is adjacent to both v and w.

If $(\delta(v), \delta(w)) = (9, 3)$, then suppose that v and w are adjacent. None of the 8 vertices in $N(u)$ that are adjacent to v can be adjacent to w (or we have a diamond), so they must all be adjacent to one of the 4 remaining vertices in $N(u)$. Hence some vertices in $N(u)$ are adjacent to more than one other vertex in $N(u)$, and there is a diamond. A similar argument holds if v and w are not adjacent.

If $(\delta(v), \delta(w)) = (6, 6)$ there is a solution and it can be constructed as follows. Divide the 12 vertices in $N(u)$ into two disjoint sets of equal cardinality $\alpha = \{a_1 \ldots a_6\}$ and $\beta = \{b_1 \ldots b_6\}$. Connect vertex a_i to b_i for $1 \leq i \leq 6$. Now connect vertex v to all vertices in α and connect w to all vertices in β. Such a graph is shown in Figure 3. □

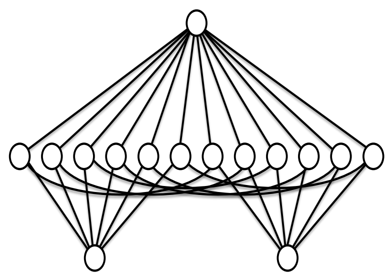

Figure 3: A diamond-free graph with 15 vertices and degree sequence $(12, 6, 6, 6, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$

Lemma 4 *If* $n = 16$ *and* $\delta(1) = 12$ *then the degree sequence is either*

1. $(12, 12, 9, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$*, or*
2. $(12, 12, 6, 6, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$*, or*
3. $(12, 9, 9, 6, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$*, or*
4. $(12, 6, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$.

Proof. Let u and $N(u)$ be defined as above, and let v, w and x be vertices that are not u and are not in $N(u)$, with corresponding degrees $\delta(v) \geq \delta(w) \geq \delta(x)$. By an argument similar to the above, G has degree sequence

$$(12, \delta(v), \delta(w), \delta(x), 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)$$

where $\delta(v)+\delta(w)+\delta(x)$ is divisible by 12. Then we must have $(\delta(v), \delta(w), \delta(x)) = (12, 12, 12)$, $(12, 9, 3)$, $(12, 6, 6)$ or $(9, 9, 6)$ or $(6, 3, 3)$. If $(\delta(v), \delta(w), \delta(x)) = (12, 12, 12)$ then there are at least 3 vertices in $N(u)$ that are adjacent to all of u, v, w and x, which is impossible since, as before, vertices in $N(u)$ must have degree 3. In all other cases there are solutions (which we do not include here). □

4 Constraint programming models

We present two constraint models for the diamond-free degree sequence problem. The first model we call model A, the second model B. In many respects the two models are very similar but what is different is how we solve them. In the subsequent descriptions we assume that we have as input the integer n, where $|V| = n$ and vertex $i \in V$. All the constraint models were implemented using the choco toolkit [9]. Further we assume that a variable x has a domain of values $dom(x)$.

4.1 Model A

Model A is based on the adjacency matrix model of a graph. We have a 0/1 constrained integer variable A_{ij} for each potential edge in the graph such that $A_{ij} = 1 \iff \{i, j\} \in E$. In addition we have constrained integer variables deg_1 to deg_n corresponding to the degrees of each vertex, such that

$$\forall_{i \in [1..n]} \ dom(deg_i) = [3 \ .. \ n-1]. \tag{1}$$

We then have constraints to ensure that the graph is simple:

$$\forall_{i \in [1..n]} \forall_{j \in [i..n]} \ A_{i,j} = A_{j,i} \tag{2}$$

$$\forall_{i \in [1..n]} \ A_{i,i} = 0. \tag{3}$$

Constraints are then required to ensure that the graph is diamond-free:

$$\forall_{i<j<k<l \in [1..n]} [A_{i,j} + A_{i,k} + A_{i,l} + A_{j,k} + A_{j,l} + A_{k,l} \leq 4]. \tag{4}$$

Finally we have constraints on the degree sequence:

$$\forall_{i \in [1 \ .. \ n]} \quad deg_i = \sum_{j=1}^{j=n} A_{i,j} \tag{5}$$

$$\forall_{i \in [1 \ .. \ n-1]} \quad deg_i \geq deg_{i+1} \tag{6}$$

$$\forall_{i \in [1 \ .. \ n]} \quad deg_i \ \mathbf{mod} \ 3 = 0 \tag{7}$$

$$\left(\sum_{i=1}^{i=n} deg_i \right) \ \mathbf{mod} \ 12 = 0. \tag{8}$$

The vertex degree variables deg_1 to deg_n are the decision variables. The constraint model uses $O(n^2)$ constrained integer variables and $O(n^4)$ constraints.

4.2 Model B

Model B is essentially model A broken into three parts, each part solved separately. The first part is to produce a degree sequence that meets the arithmetic constraints. The second part tests if that degree sequence is graphical and if it is the third part determines if there exists a diamond-free graph with that degree sequence. Therefore solving proceeds as follows.

Step 1 Generate the next degree sequence $\pi = d_1, d_2, \ldots, d_n$ that meets the arithmetical constraints. If no more degree sequences exist then terminate the process.

Step 2 If the degree sequence π is not graphical return to Step 1.

Step 3 Determine if there is a diamond-free graph with degree sequence π.

Step 4 Return to **Step 1**.

The first part of model B is then as follows. Integer variables deg_1 to deg_n correspond to the degrees of each vertex and satisfy constraints (1), (6), (7), and (8) to generate a degree sequence.

Each valid degree sequence produced is then tested to determine if it is graphical (Step 2 above) using the Havel-Hakimi algorithm. We have used the $\Theta(n^2)$ algorithm [8] although the linear Erdős–Gallai type [10] or linear Havel–Hakimi type [11] algorithms could equally well be used and would have been more efficient.

If the degree sequence is graphical (Step 3) we create an adjacency matrix with properties (2) and (3) and post the constraints (4) and (5) (diamond free with given degree sequence) where the variables deg_1 to deg_n have already been instantiated (in Step 1). Finally we are in a position to post static symmetry breaking constraints. If we are producing a graph and $deg_i = deg_j$ then these two vertices are interchangeable. Consequently we can insist that row i in the adjacency matrix is lexicographically less than or equal to row j. Therefore we post the symmetry breaking constraints:

$$\forall_{i \in [1 \,..\, n-1]}[deg_i = deg_{i+1} \Rightarrow A_i \preceq A_{i+1}] \tag{9}$$

where $\preceq$ means lexicographically less than or equal. In this second stage of solving the variables $A_{1,1}$ to $A_{n,n}$ are the decision variables.

5 Solutions

Our results are tabulated in Table 1 for $8 \le n \le 16$. All our results are produced using model B run on a machine with 8 Intel Zeon E5420 processors running at 2.50 GHz, 32Gb of RAM, with version 5.2 of linux. The longest run time was for $n = 16$ taking about 5 minutes cpu time. Included in Table 1 is the cpu time in seconds to generate all degree sequences for a given value of n.

All our results were verified. For each degree sequence the corresponding adjacency matrix was saved to file and verified to correspond to a simple

n	time	degree sequence
8	0.1	3 3 3 3 3 3 3 3
9	0.1	6 6 6 3 3 3 3 3 3
10	0.5	6 6 3 3 3 3 3 3 3 3
11	0.8	6 3 3 3 3 3 3 3 3 3 3
12	1.4	3 3 3 3 3 3 3 3 3 3 3 3
		6 6 6 6 3 3 3 3 3 3 3 3
		6 6 6 6 6 6 6 6 6 6 6 6
		9 6 6 3 3 3 3 3 3 3 3 3
13	3.7	6 6 6 3 3 3 3 3 3 3 3 3 3
		6 6 6 6 6 6 6 3 3 3 3 3 3
		6 6 6 6 6 6 6 6 6 6 6 3 3
		9 6 3 3 3 3 3 3 3 3 3 3 3
14	14.0	6 6 3 3 3 3 3 3 3 3 3 3 3 3
		6 6 6 6 6 6 3 3 3 3 3 3 3 3
		6 6 6 6 6 6 6 6 6 6 3 3 3 3
		6 6 6 6 6 6 6 6 6 6 6 6 6 6
		9 3 3 3 3 3 3 3 3 3 3 3 3 3
		9 6 6 6 6 3 3 3 3 3 3 3 3 3
		9 9 6 6 3 3 3 3 3 3 3 3 3 3
		9 9 9 3 3 3 3 3 3 3 3 3 3 3
15	107.7	6 3 3 3 3 3 3 3 3 3 3 3 3 3 3
		6 6 6 6 6 3 3 3 3 3 3 3 3 3 3
		6 6 6 6 6 6 6 6 6 3 3 3 3 3 3
		6 6 6 6 6 6 6 6 6 6 6 6 6 3 3
		9 6 6 6 3 3 3 3 3 3 3 3 3 3 3
		9 6 6 6 6 6 6 6 3 3 3 3 3 3 3
		9 6 6 6 6 6 6 6 6 6 6 6 3 3 3
		9 9 6 3 3 3 3 3 3 3 3 3 3 3 3
		9 9 6 6 6 6 6 3 3 3 3 3 3 3 3
		9 9 6 6 6 6 6 6 6 6 6 3 3 3 3
		9 9 9 6 6 6 3 3 3 3 3 3 3 3 3
		9 9 9 9 9 9 6 6 6 6 6 6 6 6 6
		12 6 6 3 3 3 3 3 3 3 3 3 3 3 3
		12 12 12 3 3 3 3 3 3 3 3 3 3 3 3
16	339.8	3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
		6 6 6 6 3 3 3 3 3 3 3 3 3 3 3 3
		6 6 6 6 6 6 6 6 3 3 3 3 3 3 3 3
		6 6 6 6 6 6 6 6 6 6 6 6 3 3 3 3
		6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
		9 6 6 3 3 3 3 3 3 3 3 3 3 3 3 3
		9 6 6 6 6 6 6 3 3 3 3 3 3 3 3 3
		9 6 6 6 6 6 6 6 6 6 6 3 3 3 3 3
		9 9 3 3 3 3 3 3 3 3 3 3 3 3 3 3
		9 9 6 6 6 6 3 3 3 3 3 3 3 3 3 3
		9 9 6 6 6 6 6 6 6 6 3 3 3 3 3 3
		9 9 6 6 6 6 6 6 6 6 6 6 6 6 3 3
		9 9 9 6 6 3 3 3 3 3 3 3 3 3 3 3
		9 9 9 6 6 6 6 6 6 6 6 6 6 3 3 3
		9 9 9 9 3 3 3 3 3 3 3 3 3 3 3 3
		9 9 9 9 6 6 6 6 6 6 6 6 3 3 3 3
		9 9 9 9 6 6 6 6 6 6 6 6 6 6 6 6
		9 9 9 9 9 6 6 6 6 6 6 6 6 6 6 3
		9 9 9 9 9 9 6 6 6 6 6 6 6 6 3 3
		12 6 3 3 3 3 3 3 3 3 3 3 3 3 3 3
		12 9 9 6 3 3 3 3 3 3 3 3 3 3 3 3
		12 12 6 6 3 3 3 3 3 3 3 3 3 3 3 3
		12 12 9 3 3 3 3 3 3 3 3 3 3 3 3 3

Table 1: Degree sequences, of length n, that meet the arithmetic constraints and have a simple diamond-free graph. Tabulated is n, cpu time in seconds to generate all sequences of length n and those sequences.

diamond-free graph that matched the degree sequence and satisfied the arithmetic constraints and this is an $\Theta(n^4)$ process. The verification software did not use any of the constraint programming code.

6 Conclusion

We have presented a new problem, the generation of all degree sequences for diamond free graphs subject to arithmetic constraints. Two models have been presented, A and B. Model A is impractical whereas model B is two stage and allows static symmetry breaking.

There are two possible improvements. The first is to model A. We might add the lexicographical constraints, as used in model B, conditionally during search. The second improvement worthy of investigation is to employ a mixed integer programming solver for the second stage of model B.

We are currently using the lists of feasible degree sequences for diamond-free graphs with 15 or 16 vertices to simplify our proofs for the classification of 4^{s_4} structures with diamond-free complements, when the number of points in the maximum number of blocks is 1 or 0 respectively. The degree sequence results for a smaller number of points will also help to simplify our existing proofs for cases where more points are in the maximum number of blocks. Ultimately we would like to use our classification to modify the extension of Stinson's algorithm for block size 4 to ensure that a block design is always produced.

In the more distant future, we would like to analyse the structures produced using our algorithm when $n > 16$. The next case is $n = 25$ and the corresponding diamond-free graphs would have up to 25 vertices.

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