

Characterization results for Steiner triple systems and their application to edge-colorings of cubic graphs

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Abstract

It is known that a Steiner triple system is projective if and only if it does not contain the four-triple configuration C_{14} . We find three configurations such that a Steiner triple system is affine if and only if it does not contain one of these configurations. Similarly, we characterize Hall triple systems using two forbidden configurations.

Our characterizations have several interesting corollaries in the area of edge-colorings of graphs. A cubic graph G is S -edge-colorable for a Steiner triple system S if its edges can be colored with points of S in such a way that the points assigned to three edges sharing a vertex

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form a triple in S . Among others, we show that all cubic graphs are S -edge-colorable for every non-projective non-affine point-transitive Steiner triple system S .

1 Introduction

Steiner triple systems form a classical notion in combinatorial design theory. Recall that a Steiner triple system S is formed by n points and several triples such that every two distinct points are contained in exactly one common triple. Steiner triple systems are simply-defined though complex and diverse combinatorial designs. One of the most classical results asserts the existence of a Steiner triple system with n points whenever $n = 1, 3(\bmod 6)$, $n \geq 3$. The amount of results on Steiner triple systems is enormous and a separate monograph [2] on the topic has recently appeared.

There are several prominent classes of Steiner triple systems, the most important ones are projective and affine Steiner triple systems. A *projective Steiner triple system* $\text{PG}(d, 2)$ is the Steiner triple system with $2^{d+1} - 1$ points corresponding to non-zero $(d + 1)$ -dimensional vectors over \mathbb{Z}_2 for $d \geq 1$. Three such vectors form a triple of $\text{PG}(d, 2)$ if they sum to the zero vector. The smallest Steiner triple system is the projective system $\text{PG}(1, 2)$, comprised of three points forming a single triple. It is referred to as the *trivial* Steiner triple system, while larger Steiner triple systems are called *non-trivial*. The smallest non-trivial projective Steiner triple system is $\text{PG}(2, 2)$, the Fano plane, which is denoted by S_7 . An *affine Steiner triple system* $\text{AG}(d, 3)$ is the Steiner triple system with 3^d points corresponding to d -dimensional vectors over \mathbb{Z}_3 for $d \geq 1$. Three such vectors form a triple of $\text{AG}(d, 3)$ if they sum to the zero vector. The smallest affine Steiner triple system, $\text{AG}(1, 3)$, is isomorphic to the trivial Steiner triple system. The smallest non-trivial affine Steiner triple system, $\text{AG}(2, 3)$, is the unique Steiner triple system with nine points and is denoted by S_9 .

It is natural to ask whether these two classes of Steiner triple systems can be characterized in terms of well-described forbidden substructures (as for instance, it is known that a graph is planar if and only if it does not contain a subdivision of one of the graphs $K_{3,3}$ or K_5). To be more precise, a *configuration* C is formed by points and triples such that each pair of point is in at most one of the triples, and a Steiner triple system S *contains* C if there is an injective mapping of the points of C to the points of S such that

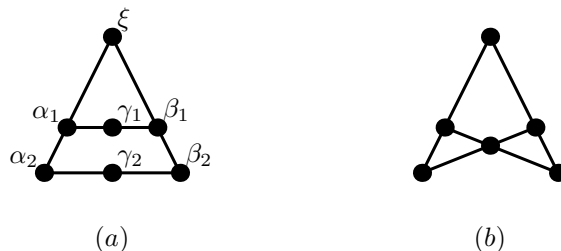


Figure 1: (a) The configuration C_{14} and (b) the Pasch configuration C_{16} .

triples of points of C are mapped to triples of points of S .

The solution to the just stated problem is easy to find for the class of projective Steiner triple systems. Two four-triple configurations play important roles in this characterization: the first one is the *configuration* C_{14} formed by seven distinct points ξ , α_1 , α_2 , β_1 , β_2 , γ_1 and γ_2 together with four triples $\{\xi, \alpha_1, \alpha_2\}$, $\{\xi, \beta_1, \beta_2\}$, $\{\alpha_1, \beta_1, \gamma_1\}$ and $\{\alpha_2, \beta_2, \gamma_2\}$; see Figure 1(a). The second one is the *configuration* C_{16} , known as the *Pasch configuration*, which is formed by six points and four triples; see Figure 1(b).

Clearly, the configuration C_{14} cannot be contained in a projective Steiner triple system. The converse is also true: Stinson and Wei [11] established that a Steiner triple system S with n points is projective if and only if it contains $\frac{1}{24}n(n-1)(n-3)$ distinct copies of the Pasch configuration. By a counting argument given in [5], if S contains less than $\frac{1}{24}n(n-1)(n-3)$ copies of the Pasch configuration, then it must contain a configuration isomorphic to C_{14} . We state this observation as a separate theorem.

Theorem 1 (Grannell et al. [5] and Stinson et al. [11]). *A Steiner triple system S is projective if and only if it contains no configuration C_{14} .*

However, we were not able to find such a simple argument characterizing affine Steiner triple systems in the literature. In Section 5, we show that a Steiner triple system is affine unless it contains one of the three configurations depicted in Figure 2, namely the Pasch configuration C_{16} , the *configuration* C_S^1 and the *configuration* C_S^2 (the last two configurations are obtained from the squashed square configuration C_S introduced in Section 2).

Still a finer distinction between affine and non-affine Steiner triple systems can be achieved. A prominent class of Steiner triple systems are Hall triple systems: a Steiner triple system S is a *Hall triple system* if for every point

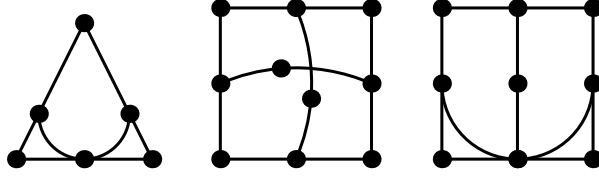


Figure 2: The three forbidden configuration for affine Steiner triple systems: the configurations C_{16} , C_S^1 and C_S^2 (from left to right).

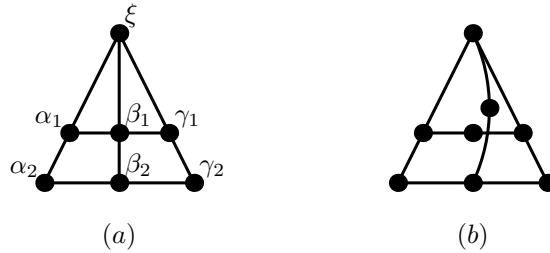


Figure 3: (a) The mitre configuration and (b) the anti-mitre configuration C_A .

x of S , there exists an automorphism of S that is involution and its only fixed point is x . Hall [6] showed that a Steiner triple system is a Hall triple system if and only if every Steiner triple system induced by the points of two non-disjoint triples of S is isomorphic to S_9 . Recall that the Steiner triple system *induced* by a set X of the points of S is the smallest Steiner triple system S' such that S' contains all the points of X and all triples of S' are also triples of S . Hence, Hall triple systems look “locally” as affine Steiner triple systems and it can seem hard to distinguish these two classes in terms of forbidden substructures. Also note that there are examples of Hall triple systems that are not affine Steiner triple systems for every $n = 3^d$, $d \geq 4$, unlike in the case of affine Steiner triple systems: if every two non-disjoint triples of S induce a Steiner triple system isomorphic to S_7 , then S must be projective.

It is known that an n -point Steiner triple system is a Hall triple system if and only if it contains $\frac{n(n-1)(n-3)}{12}$ configurations isomorphic to the mitre configuration [2] which is depicted in Figure 3(a) (the points are labeled for future references). Since no Steiner triple system can contain more than

$\frac{n(n-1)(n-3)}{12}$ copies of the mitre configuration, Hall triple systems are those which contains the largest number of configurations isomorphic to the mitre configuration.

Let us turn back to our results. As we mentioned, a Steiner triple system S is affine if and only if it contains neither of the configurations C_{16} , C_S^1 and C_S^2 . None of Hall triple systems can contain the configuration C_{16} or the anti-mitre configuration C_A (see Figure 3(b)) as neither of them is contained in the Steiner triple system S_9 . The converse is also true as we show in Section 5: a Steiner triple system is a Hall triple system if and only if it does not contain the configuration C_{16} or C_A , and a Hall triple system is affine if and only if it contains none of the configuration C_S^1 and C_S^2 . With the additional assumption that a Steiner triple system S is not projective, we can remove the configuration C_{16} from the list of forbidden configurations both for affine Steiner triple systems and Hall triple systems. We also note that every Steiner triple system containing the configuration C_A also contains one of the configurations C_S^1 and C_S^2 (this seems to be a non-trivial fact which we state as Lemma 6).

1.1 Edge-colorings of cubic graphs

Edge-colorings of cubic (bridgeless) graphs form a prominent topic in graph theory because of its close relation to deep and important problems such as Four Color Theorem, Cycle Double Cover Conjecture and many others. By Vizing's theorem [12], the edges of every cubic graph can be colored with three or four colors in such a way that the edges meeting at the same vertex receive distinct colors. Non-trivially connected cubic graphs (usually the cyclic 4-edge-connectivity is required) such that their edges cannot be colored with three colors are called *snarks*.

Archdeacon [1] proposed to study edge-colorings of cubic graphs by the points of Steiner triple systems. Steiner triple systems seem to be general enough to "edge-color" most of cubic graphs and still well-structured enough to provide us with new results on cubic graphs. In particular, this notion extends the notion of the ordinary edge-colorings among the lines of well-studied locally injective homomorphisms.

The points of a Steiner triple system S are assigned to the edges of a cubic graph G in such a way that the edges incident with the same vertex are assigned three distinct points that form a triple of S . Edge-colorings with this property are called *S-edge-colorings* and G is said to be *S-edge-*

colorable. A natural question is for which cubic graphs G and which Steiner triple systems S , there exists an S -edge-coloring of G . In particular, whether there exists a Steiner triple system S such that every simple cubic graph (bridgeless or not) is S -edge-colorable; such a system S is called *universal*.

Grannell et al. [4] established the existence of a universal Steiner triple system with 381 points. Later, Pál and Škoviara [10] showed that there exists a universal Steiner triple system with 21 points (the system they considered is the direct product of the Fano plane and the trivial Steiner triple system). One of the corollaries of our results is the existence of a universal Steiner triple system with 13 points. Let us note that no Steiner triple system with less than 13 points can be universal [7].

We now survey further results on edge-colorings of cubic graphs with points of Steiner triple systems. Let us emphasize that all cubic graphs that we consider in this paper are connected and they can contain bridges unless stated otherwise. On the other hand, they never contain loops or parallel edges. This assumption does not decrease generality of our results: a cubic graph with a loop does not have an S -edge-coloring for any Steiner triple system S since the points assigned to the edges incident with the vertex with the loop cannot form a triple in S . If a cubic graph G contains a pair of parallel edges e_1 and e_2 between two vertices v_1 and v_2 , let G' be the graph obtained from G by removing e_1 and e_2 and identifying the other edges incident with v_1 and v_2 . It is straightforward to verify that G is S -edge-colorable if and only if G' is. Hence, we can subsequently eliminate the pairs of all parallel edges in a cubic graph. Note that loops can appear during this elimination process yielding that the original graph is not S -edge-colorable for any Steiner triple system S .

Fu [3] showed that every bridgeless cubic graph of order at most 189 and of genus at most 24 are S_7 -edge-colorable. A stronger result was obtained by Holroyd and Škoviara [7] who showed that a cubic graph G is S -edge-colorable for a non-trivial projective Steiner triple system S if and only if it is bridgeless. In particular, all bridgeless cubic graphs are S_7 -edge-colorable. The condition on G being bridgeless can be easily seen to be necessary since an edge-coloring of G with the points of a projective Steiner triple system $\text{PG}(d, 2)$ can be viewed as a nowhere-zero flow over \mathbb{Z}_2^{d+1} . It is well-known that a graph has a nowhere-zero flow if and only if it is bridgeless.

A characterization of cubic graphs that are S -edge-colorable for a non-projective Steiner triple system S has been offered as a conjecture (see Conjecture 1). One of the obstacles for the existence of an S -edge-coloring is

the notion of a bipartite end which we now introduce. If a cubic graph G has bridges it can be split along its bridges into 2-connected *blocks*, each incident with one or more bridges. Each bridge is split into two *half-edges*, each half-edge incident with one of the blocks. Note that some blocks can be formed by a single vertex incident with three half-edges; such blocks are called *trivial*. A block incident with a single half-edge is called *end*. Let H be an end of a cubic graph and H' the graph obtained from H by suppressing the vertex incident with the half-edge. Hence, H' is a bridgeless cubic graph which can contain a single pair of parallel edges (one of those is the contracted edge). We say that H is a *bipartite end* if the graph H' is bipartite, H is a *3-edge-colorable end* if H' is 3-edge-colorable (in the usual sense), and H is *hamiltonian* if H' has a Hamilton cycle avoiding the edge obtained by suppressing the vertex incident with the half-edge.

We can now state the conjectured characterization of cubic graphs that are S -edge-colorable with a Steiner triple system S .

Conjecture 1 (Holroyd and Škoviera [7], Conjecture 1.4). *Let S be a non-projective Steiner triple system. A cubic graph G is S -edge-colorable unless G has a bipartite end and S is affine.*

If a cubic graph G has a bipartite end H and a Steiner triple system S is affine, an easy linear algebra argument yields that the two edges of H incident with the bridge must be colored with the same point of S [7]. Hence, G cannot be S -edge-colored. The conjecture of Holroyd and Škoviera asserts this to be the only obstacle for the existence of an S -edge-coloring unless S is projective.

As a corollary of our characterization results on Steiner triple systems, we can prove Conjecture 1 with an additional assumption that the Steiner triple system S is *point-transitive*, i.e., for every two points x and y of S , there exists an automorphism of S that maps x to y . In fact, for non-trivial point-transitive Steiner triple systems S , we can characterize cubic graphs G that are S -edge-colorable: if S is projective, G is S -edge-colorable if and only if G is bridgeless (this follows from the results of [7]). If S is affine, G is S -edge-colorable if and only if G has no bipartite end (this solves an open problem from [7, 10] whether every cubic graph with no bipartite end is AG(2, 3)-edge-colorable). Finally, if S a non-trivial point-transitive Steiner triple system that is neither projective nor affine, then G is always S -edge-colorable.

Since there exists a point-transitive Steiner triple system with 13 vertices that is neither projective nor affine, we can infer from our results the exis-

tence of a universal 13-point Steiner triple system. Since the only smaller Steiner triple systems are the trivial Steiner triple system, the projective Steiner triple system $S_7 = \text{PG}(2, 2)$ and the affine Steiner triple system $S_9 = \text{AG}(2, 3)$, the point-transitive Steiner triple system with 13 points is the universal Steiner triple system with the smallest number of points (this solves an open problem from [4] to determine the number of points of the smallest universal Steiner triple system).

2 Notation

In this section, we introduce some additional notation related to Steiner triple systems. If S is a Steiner triple system, we find convenient to have a special notation for the point z forming a triple with two given distinct points x and y : such point z is denoted by $x \oplus y$ throughout the paper. For instance, in C_{14} depicted in Figure 1(a), $\xi = \beta_1 \oplus \beta_2$. Note that the operation \oplus is commutative and need not be associative, i.e., the points $x_1 \oplus (x_2 \oplus x_3)$ and $(x_1 \oplus x_2) \oplus x_3$ could be distinct.

The set X of points of a Steiner triple system S is said to be *independent* if for every $x \in X$, the Steiner triple system S' induced by $X \setminus \{x\}$ in S does not contain x . For instance, a set X of points of an affine Steiner triple system is independent if and only if X is affinely independent over \mathbb{Z}_3 .

We now introduce another notion of containment of configurations in Steiner triple systems and relate it to the standard notion. Let C be a configuration, as defined earlier, with a distinguished pair (a, b) of its points. As an example, consider the squashed square configuration C_S depicted in Figure 4 with $a = x_{\alpha\beta}$ and $b = x_{\gamma\delta}$. We say that a Steiner triple system S *homomorphically contains* the configuration C if there exists a mapping φ of points of C to the points of S such that every triple of C is injectively mapped onto a triple of S and $\varphi(a) \neq \varphi(b)$. Note that we do not require the mapping φ to be injective but we require that no two points of the same triple of C are mapped to the same point of S and that the points a and b are mapped to distinct points of S .

In Sections 3 and 4, when proving our characterization theorems, it will be more convenient to show that a given Steiner triple system homomorphically contains C_S , rather than it contains one of the configurations C_S^1 and C_S^2 . Let us realize that the two statements are equivalent.

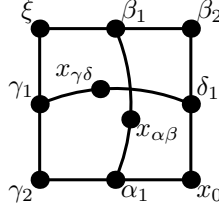


Figure 4: The squashed square configuration C_S . Note that it is required that $\varphi(x_{\alpha\beta}) \neq \varphi(x_{\gamma\delta})$ but the other pairs of points can coincide in a Steiner triple system.

Lemma 2. *A Steiner triple system S homomorphically contains the squashed square configuration C_S if and only if S contains the configuration C_S^1 or the configuration C_S^2 .*

Proof. If S contains the configuration C_S^1 or the configuration C_S^2 , then S homomorphically contains C_S . In the rest, we focus on proving the converse implication. Let X be the set of points of the squashed square configuration C_S ; the points of C_S are denoted as in Figure 4. Assume that S homomorphically contains the squashed square configuration C_S and let φ be the mapping from X to the points of C_S as in the definition of homomorphical containment.

We first show that $\varphi(\xi)$ is distinct from $\varphi(x)$ for every $x \in X \setminus \{\xi\}$. By symmetry, it is enough to consider that $\varphi(\xi)$ would be equal to $\varphi(\alpha_1)$, $\varphi(x_0)$ or $\varphi(x_{\alpha\beta})$ and obtain a contradiction. If $\varphi(\xi) = \varphi(\alpha_1)$, then $\varphi(x_0) = \varphi(\gamma_1)$ since $\gamma_2 = \xi \oplus \gamma_1 = \alpha_1 \oplus x_0$ (in more detail, since $\varphi(\xi) = \varphi(\alpha_1)$ and S contains the triples $\{\varphi(\gamma_2), \varphi(\xi), \varphi(\alpha_1)\}$ and $\{\varphi(\gamma_2), \varphi(\alpha_1), \varphi(x_0)\}$, it must also hold that $\varphi(\alpha_1) = \varphi(x_0)$). Similarly, the equality $\beta_1 = \xi \oplus \beta_2 = \alpha_1 \oplus x_{\alpha\beta}$ implies that $\varphi(\beta_2) = \varphi(x_{\alpha\beta})$, and $\delta_1 = x_0 \oplus \beta_2 = \gamma_1 \oplus x_{\gamma\delta}$ yields that $\varphi(\beta_2) = \varphi(x_{\gamma\delta})$. We infer that $\varphi(x_{\alpha\beta}) = \varphi(x_{\gamma\delta}) = \varphi(\beta_2)$ which is impossible.

If it held $\varphi(\xi) = \varphi(x_0)$, then it would also hold that $\varphi(\alpha_1) = \varphi(\gamma_1)$ and $\varphi(\beta_1) = \varphi(\delta_1)$. Consequently, $\varphi(x_{\alpha\beta}) = \varphi(x_{\gamma\delta})$ contrary to the definition of homomorphical containment.

Finally, if $\varphi(\xi) = \varphi(x_{\alpha\beta})$, we obtain $\varphi(\alpha_1) = \varphi(\beta_2)$. From this it follows that $\varphi(x_{\alpha\beta}) = \varphi(x_{\gamma\delta})$ similarly to the case where $\varphi(\xi) = \varphi(\alpha_1)$ with β_2 playing the role of ξ .

If φ maps X to ten distinct points of S , i.e., φ is injective, then S contains the configuration C_S^1 . Otherwise, two of the points of X are mapped to the

same point of S . As the points ξ , x_0 , β_2 and γ_2 are mapped to distinct points of S , $\varphi(\alpha_1) \neq \varphi(\delta_1)$ (otherwise, $x_0 = \alpha_1 \oplus \gamma_2 = \delta_1 \oplus \beta_2$ implies that $\varphi(\beta_2) = \varphi(\gamma_2)$). By the symmetry, we can assume that $\varphi(\alpha_1) = \varphi(x_{\gamma\delta})$. It is now straightforward to check that no other two points of X can be mapped by φ to the same point of S and thus S contains the configuration C_S^2 . We conclude that if S homomorphically contains the squashed-square configuration C_S , then S contains one of the configurations C_S^1 and C_S^2 . \square

3 Forbidden configurations in Hall triple systems

We split the proof of our characterization results into two parts. In this section, we deal with Hall triple systems and in the next section, we focus on non-Hall triple systems.

Lemma 3. *Every Hall triple system S that is not affine homomorphically contains the squashed-square configuration C_S .*

Proof. Let us first introduce some additional notation that we use throughout the proof. Fix an arbitrary point of S ; we refer to this point as to the *zero* and it is denoted by $\underline{0}$. The other points of S are said to be *non-zero*.

For a set M of non-zero points of S , $L(M)$ is the Steiner triple system induced by $M \cup \{\underline{0}\}$. If M contains a single point, then $L(M)$ is isomorphic to the trivial Steiner triple system. Observe that if a set M of non-zero points of S is such that $a \notin L(M \setminus \{a\})$ for every $a \in M$, then it is independent, as defined in Section 2. Since S is Hall, $L(M)$ is isomorphic to S_9 for every two-point set M such that $M \cup \{\underline{0}\}$ is independent. On the other hand, since S is not affine there exists an independent set M such that $L(M)$ is not an affine Steiner triple system. Let $M = \{e_1, \dots, e_d\}$ be an inclusion-wise minimal independent set for which $L(M)$ is not affine. Note that $d \geq 3$.

Let $V = \mathbb{Z}_3^d$ and let V^0 be the set of the vectors of V with at least one coordinate equal to zero. Define a mapping $\phi : V^0 \rightarrow L(M)$ as follows: the zero-vector is mapped to $\underline{0}$ and the unit vectors are mapped to the points of M . The mapping ϕ is then extended to the remaining vectors of V^0 in such a way that whenever the vectors \vec{a} , \vec{b} and \vec{c} have at least one common coordinate equal to zero and sum to zero, then $\phi(\vec{a})$, $\phi(\vec{b})$ and $\phi(\vec{c})$ form a triple in $L(M)$. Since each of the systems $L(M \setminus \{e_i\})$, $i = 1, \dots, d$, is affine, such an extension of ϕ to V^0 is well-defined and unique.

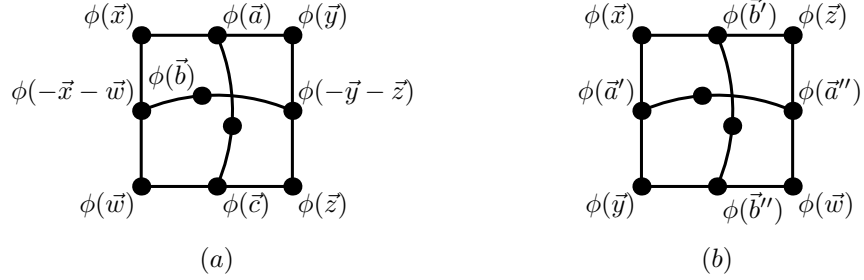


Figure 5: Two squashed-square configurations constructed in the proof of Lemma 3.

Since $L(M)$ is not affine, the mapping cannot be extended to the whole set V in such a way that each triple of vectors summing to zero is mapped to a triple of $L(M)$. There could be several obstacles for the existence of such an extension. The simplest one is that there exist three vectors \vec{a} , \vec{b} and \vec{c} of V^0 such that $\vec{a} + \vec{b} + \vec{c} = \vec{0}$ but the points $\phi(\vec{a})$, $\phi(\vec{b})$ and $\phi(\vec{c})$ do not form a triple in $L(M)$. By the definition of ϕ , the vectors \vec{a} , \vec{b} and \vec{c} cannot have a common coordinate equal to zero. Hence, there exist three distinct indices i , j and k such that $\vec{a}_i = \vec{b}_j = \vec{c}_k = 0$ but the coordinates \vec{a}_j , \vec{a}_k , \vec{b}_i , \vec{b}_k , \vec{c}_i and \vec{c}_j are non-zero.

We now define four vectors \vec{w} , \vec{x} , \vec{y} and \vec{z} based on the vectors \vec{a} , \vec{b} , \vec{c} . The i -th coordinates of the vectors are $\vec{x}_i = \vec{y}_i = \vec{z}_i = 0$ and $\vec{w}_i = -\vec{c}_i$; the j -th coordinates are $\vec{x}_j = \vec{w}_j = 0$, $\vec{y}_j = -\vec{a}_j$ and $\vec{z}_j = -\vec{c}_j$; and the k -th coordinates are $\vec{x}_k = \vec{y}_k = \vec{a}_k$ and $\vec{w}_k = \vec{z}_k = 0$. The remaining coordinates are set as $\vec{x}_t = -\vec{a}_t$, $\vec{y}_t = 0$, and $\vec{w}_t = \vec{z}_t = \vec{c}_t$ for $t \notin \{i, j, k\}$. Note that $\vec{a} + \vec{x} + \vec{y} = \vec{0}$ and $\vec{c} + \vec{w} + \vec{z} = \vec{0}$. In addition, the vectors \vec{x} and \vec{w} have a common coordinate equal to zero, and similarly the pairs of vectors \vec{x} and \vec{y} , \vec{y} and \vec{z} , and \vec{w} and \vec{z} . Observe also that the j -th coordinate of \vec{b} and $-(\vec{x} + \vec{w})$ is zero, and $\vec{b} + (-\vec{x} - \vec{w}) + (-\vec{y} - \vec{z}) = \vec{0}$. Since $\phi(\vec{b}) \neq \phi(\vec{a}) \oplus \phi(\vec{c})$ by our assumption, the configuration looks as depicted in Figure 5(a). Hence, we have exhibited the squashed-square configuration in S .

Assume now that for every triple \vec{a} , \vec{b} and \vec{c} of vectors of V^0 with $\vec{a} + \vec{b} + \vec{c} = \vec{0}$, the points $\phi(\vec{a})$, $\phi(\vec{b})$ and $\phi(\vec{c})$ form a triple in $L(M)$. Our next aim is to try to extend ϕ to V by defining $\phi(\vec{a}) = \phi(\vec{a}') \oplus \phi(\vec{a}'')$ for vectors $\vec{a} \in V \setminus V^0$ and $\vec{a}', \vec{a}'' \in V^0$ such that $\vec{a} + \vec{a}' + \vec{a}'' = \vec{0}$. This extension would be possible unless there existed four vectors $\vec{a}', \vec{a}'', \vec{b}', \vec{b}'' \in V^0$ such that $\vec{a}' + \vec{a}'' = \vec{b}' + \vec{b}''$

and $\phi(\vec{a}') \oplus \phi(\vec{a}'') \neq \phi(\vec{b}') \oplus \phi(\vec{b}'')$. Assume the existence of such vectors $\vec{a}', \vec{a}'', \vec{b}'$ and \vec{b}'' .

We next find four vectors $\vec{w}, \vec{x}, \vec{y}$ and \vec{z} in V^0 such that $\vec{a}' + \vec{x} + \vec{y} = \vec{0}$, $\vec{b}' + \vec{x} + \vec{z} = \vec{0}$, $\vec{a}'' + \vec{w} + \vec{z} = \vec{0}$ and $\vec{b}'' + \vec{y} + \vec{w} = \vec{0}$; see Figure 5(b). Thus S contains the squashed-square configuration. Note that $\vec{a}' + \vec{a}'' = \vec{b}' + \vec{b}'' \notin V^0$ by our assumptions. In particular, the vectors \vec{a}' and \vec{a}'' do not have the same coordinate equal to zero and the same also holds for \vec{b}' and \vec{b}'' . If we fix arbitrarily one of the coordinates of \vec{w} , say \vec{w}_i , then the i -th coordinates of the vectors \vec{x}, \vec{y} and \vec{z} are uniquely determined: $\vec{y}_i = -(\vec{b}'_i + \vec{w}_i)$, $\vec{z}_i = -(\vec{a}''_i + \vec{w}_i)$ and $\vec{x}_i = -(\vec{a}'_i + \vec{y}_i) = -(\vec{b}'_i + \vec{z}_i)$ (the last two expressions are the same since $\vec{a}'_i + \vec{a}''_i = \vec{b}'_i + \vec{b}''_i$). Similarly, fixing the i -th coordinate of \vec{x} determines the i -th coordinate of the vectors \vec{y}, \vec{z} and \vec{w} .

First we assume that the vectors \vec{a}' and \vec{b}' have the same coordinate equal to zero, say $\vec{a}'_i = \vec{b}'_i = 0$. We set $\vec{x}_i = 0$. This determines the i -th coordinates of the vectors \vec{w}, \vec{y} and \vec{z} . In particular, $\vec{y}_i = 0$ and $\vec{z}_i = 0$. Since $\vec{a}'', \vec{b}'' \in V^0$, there exist i' and i'' such that $\vec{a}''_{i'} = 0$ and $\vec{b}''_{i''} = 0$ (the indices i' and i'' need not be distinct). Since the vectors \vec{a}' and \vec{a}'' do not have a common coordinate equal to zero, $i \neq i'$. Analogously, $i \neq i''$. Set $\vec{w}_{i'} = 0$ and $\vec{w}_{i''} = 0$. The remaining coordinates of the vector \vec{w} are chosen arbitrarily. This completely determines all the vectors $\vec{w}, \vec{x}, \vec{y}$ and \vec{z} . All the vectors $\vec{w}, \vec{x}, \vec{y}$ and \vec{z} are in V^0 and they satisfy the above constraints. Analogously, we can handle the cases where the vectors \vec{a}' and \vec{b}'' , \vec{a}'' and \vec{b}' , or \vec{a}'' and \vec{b}'' have the same coordinate equal to zero.

We now assume that no pair of the vectors $\vec{a}', \vec{a}'', \vec{b}'$ and \vec{b}'' have the same coordinate equal to zero. Let i', i'', j' and j'' be the indices such that $\vec{a}'_{i'} = 0$, $\vec{a}''_{i''} = 0$, $\vec{b}'_{j'} = 0$ and $\vec{b}''_{j''} = 0$. Choose $\vec{x}_{i'} = \vec{x}_{j'} = 0$ and $\vec{w}_{i''} = \vec{w}_{j''} = 0$. This determines the i' -th, i'' -th, j' -th and j'' -th coordinate of all the vectors $\vec{w}, \vec{x}, \vec{y}$ and \vec{z} . The remaining coordinates of the vector \vec{x} are chosen arbitrarily and the remaining coordinates of the other vectors are determined by this choice. Again, we have obtained the configuration depicted in Figure 5(b).

Hence, we have excluded the existence of the vectors $\vec{a}', \vec{a}'', \vec{b}'$ and \vec{b}'' . Therefore, we conclude that the mapping ϕ can be extended to $V \setminus V^0$ in such a way that $\phi(\vec{x}) = \phi(\vec{x}') \oplus \phi(\vec{x}'')$ for all vectors $\vec{x} \in V$ and $\vec{x}', \vec{x}'' \in V^0$ with $\vec{x} + \vec{x}' + \vec{x}'' = \vec{0}$. Since $L(M)$ is not affine, there must exist three vectors \vec{a}, \vec{b} and \vec{c} in V such that $\vec{a} + \vec{b} + \vec{c} = \vec{0}$ and $\phi(\vec{c}) \neq \phi(\vec{a}) \oplus \phi(\vec{b})$ for this (uniquely defined) mapping ϕ .

If $\vec{a} = \vec{0}$, choose arbitrary two vectors \vec{b}' and \vec{b}'' in V^0 such that $\vec{b} + \vec{b}' + \vec{b}'' =$

$\vec{0}$. Hence, $\vec{c} + (\vec{a} + \vec{b}') + (\vec{a} + \vec{b}'') = \vec{0}$ and both $\vec{a} + \vec{b}'$ and $\vec{a} + \vec{b}''$ are contained in V^0 . Since S is Hall and $\phi(\vec{x}) = \phi(\vec{x}') \oplus \phi(\vec{x}'')$ for all vectors $\vec{x} \in V$ and $\vec{x}', \vec{x}'' \in V^0$ with $\vec{x} + \vec{x}' + \vec{x}'' = \vec{0}$, it follows that $\phi(\vec{c}) = \phi(\vec{a}) \oplus \phi(\vec{b})$, a contradiction. Hence, $\vec{a} \neq \vec{0}$.

Since the vectors \vec{a} , \vec{b} and \vec{c} are distinct, there exists i such that \vec{a}_i , \vec{b}_i and \vec{c}_i are distinct. By symmetry, we can assume that $\vec{a}_i = 0$. We aim to define four vectors \vec{w} , \vec{x} , \vec{y} and \vec{z} that would form the configuration depicted in Figure 5(a). Set $\vec{x}_i = \vec{y}_i = \vec{z}_i = 0$ and $\vec{w}_i = -\vec{c}_i$. Let j be the index such that $\vec{a}_j \neq 0$ and set $\vec{x}_j = \vec{w}_j = 0$, $\vec{y}_j = -\vec{a}_j$ and $\vec{z}_j = -\vec{c}_j$. The remaining coordinates of the vectors \vec{w} , \vec{x} , \vec{y} and \vec{z} are chosen in such a way that $\vec{a} + \vec{x} + \vec{y} = \vec{0}$ and $\vec{c} + \vec{w} + \vec{z} = \vec{0}$. Observe that $\vec{x} + \vec{w} \in V^0$ and $\vec{y} + \vec{z} \in V^0$. Hence, $\phi(\vec{b}) = \phi(-\vec{x} - \vec{w}) \oplus \phi(-\vec{y} - \vec{z})$ since $\vec{b} + (-\vec{x} - \vec{w}) + (-\vec{y} - \vec{z}) = \vec{0}$. We conclude that the constructed configuration matches that depicted in Figure 5(a). This finishes the proof that if the mapping ϕ cannot be extended to the whole set V , then S homomorphically contains the squashed-square configuration. Hence, the proof of the lemma is complete. \square

4 Forbidden configurations in other Steiner triple systems

In the previous section, we have dealt with Hall triple systems, and in this section we consider non-Hall triple systems. In the next section, the results of the previous and this section are combined to obtain characterizations of affine Steiner triple systems and Hall triple systems in terms of forbidden subconfigurations.

Our aim is to show that every non-projective Steiner triple system that is not Hall contains the anti-mitre configuration C_A , depicted in Figure 3(b). As the first step, we establish that if a Steiner triple system S does not contain C_A , then every three independent points of S induce a system isomorphic to S_7 or S_9 .

Lemma 4. *If a Steiner triple system S does not contain the anti-mitre configuration, then every three independent points of S induce a Steiner triple system isomorphic to S_7 or S_9 .*

Proof. Let A , B and C be three independent points of S and let $a = B \oplus C$, $b = A \oplus C$ and $c = A \oplus B$; see Figure 6(a). Note that all the points A , B ,

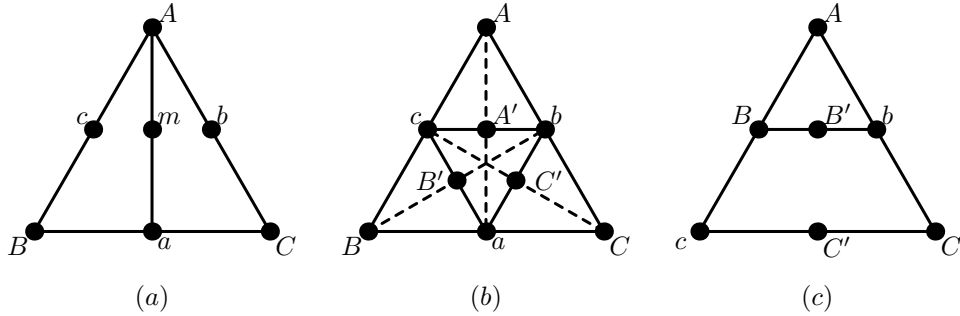


Figure 6: The configurations considered in the proof of Lemma 4.

C , a , b and c are mutually distinct. We next consider two cases.

- **The points a , b and c form a triple of S .**

Let $m = A \oplus a$. If $m \oplus c$ is neither b nor C , we obtain a configuration isomorphic to the anti-mitre configuration. Since the points a , b and c form a triple in S , $m \oplus c$ cannot be b . Hence, $m \oplus c = C$. A symmetric argument yields that $m \oplus b = B$. So the points A , B and C induce a Steiner triple system isomorphic to S_7 .

- **The points a , b and c are independent.**

Let $A' = b \oplus c$, $B' = a \oplus c$ and $C' = a \oplus b$. Since a , b and c are independent, all the points A, B, C, a, b, c, A', B' and C' are mutually distinct. Since S contains no anti-mitre configuration, the point A' is either a or $A \oplus a$. We have just excluded the former case. Hence, $A' = A \oplus a$. By the symmetry, we deduce that $B' = B \oplus b$ and $C' = C \oplus c$.

Therefore we obtain the configurations depicted in Figures 6(b) and (c). Again, since S does not contain the anti-mitre configuration, the point B' is equal to either C' or $A \oplus C'$. Since the points B' and C' are distinct, it holds that $B' = A \oplus C'$. By the symmetry, $B = A' \oplus C'$ and $C = A' \oplus B'$. We conclude that the points A, B, C, a, b, c, A', B' and C' induce a Steiner triple system isomorphic to S_9 .

□

Using Lemma 4, we can now show that every non-projective Steiner triple that is not Hall contains the anti-mitre configuration.

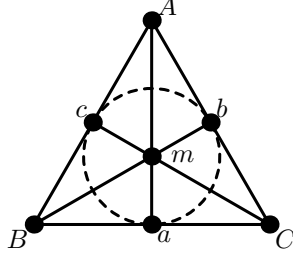


Figure 7: Notation used in the proof of Lemma 5.

Lemma 5. *Every Steiner triple system S that is not projective and that is not a Hall triple system contains the anti-mitre configuration C_A .*

Proof. Assume for the sake of contradiction that S which is neither a projective Steiner triple system nor a Hall triple system does not contain the configuration C_A . By Lemma 4, every three independent points induce a Steiner triple system isomorphic to S_7 or S_9 . If all such induced systems are isomorphic to S_7 , then S is projective. On the other hand, since S is not a Hall triple system, all of them cannot be isomorphic to S_9 either. Hence, there exist four independent points A, B, C and D such that the points A, B and C induce a Steiner triple system S' isomorphic to S_7 , and there exist two independent points t and t' of S' such that the points D, t and t' induce a Steiner triple system isomorphic to S_9 .

The Steiner triple system induced by A, B and C is isomorphic to S_7 . We set $a = B \oplus C$, $b = A \oplus C$, $c = A \oplus B$ and $m = A \oplus a = B \oplus b = C \oplus c$; see Figure 7. Let $D_A = A \oplus D$, $D_B = B \oplus D$, $D_C = C \oplus D$, $D_a = a \oplus D$, $D_b = b \oplus D$, $D_c = c \oplus D$ and $D_m = m \oplus D$. Note that all the seven points D_A, \dots, D_m are distinct and neither of them is contained in S' .

We now color the triples of S' with red and blue based on the following rule: if $\{t, t', t''\}$ is a triple of S' and the points t, t' and D induce a Steiner triple system isomorphic to S_7 , color the triple $\{t, t', t''\}$ red; otherwise, the points induce a Steiner triple system isomorphic to S_9 and the triple $\{t, t', t''\}$ is colored blue. This coloring is well-defined and by our assumptions, at least one of the seven triples of S' is blue. Observe now that S' contains a point such that all the three triples containing this point have the same color. By symmetry, we can assume that m is such a point and consider only the following two cases.

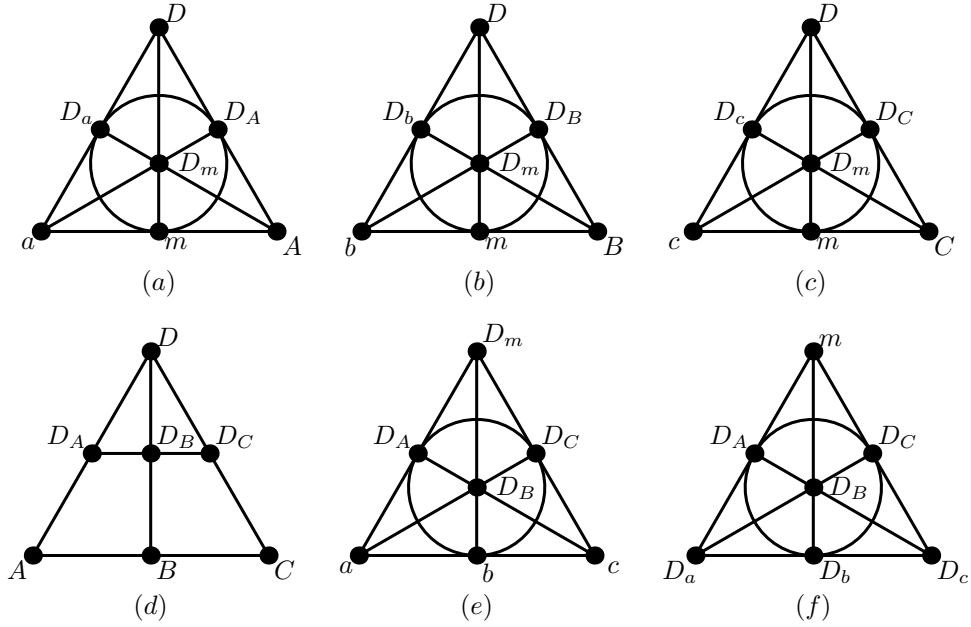


Figure 8: Configurations contained in S in the case where all the sets $\{A, a, D\}$, $\{B, b, D\}$ and $\{C, c, D\}$ induce Steiner triple systems isomorphic to S_7 .

- **The sets $\{A, a, D\}$, $\{B, b, D\}$ and $\{C, c, D\}$ induce Steiner triple systems isomorphic to S_7 .**

Observe that $D_A = m \oplus D_a = D_m \oplus a$, $D_B = m \oplus D_b = D_m \oplus b$ and $D_C = m \oplus D_c = D_m \oplus c$; see Figure 8(a), (b) and (c) respectively. Since there exist two points of S' that with D induce a Steiner triple system isomorphic to S_9 , we can assume by symmetry that the points $\{a, b, D\}$ induce a system isomorphic to S_9 .

Note that the points D_A, D_B and D_C cannot form a triple: otherwise, the point C would be contained in the Steiner triple system induced by A, B and D contradicting our choice of A, B, C and D as four independent points; see Figure 8(d). Therefore, the Steiner triple system induced by D_m, a and b is not affine and thus it is isomorphic to S_7 ; see Figure 8(e). Similarly, the Steiner triple system induced by m, D_a and D_b is isomorphic to S_7 (Figure 8(f)). This readily implies that the points b and D_b must be the same since they both are the point

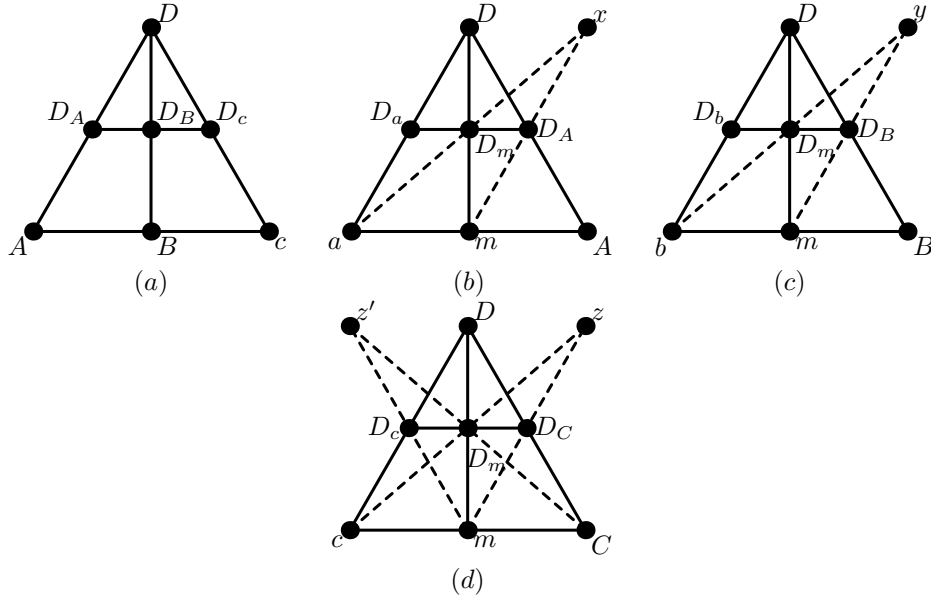


Figure 9: Configurations contained in S in the case where D and every two points of S' induce a Steiner triple systems isomorphic to S_9 .

$D_A \oplus D_C$. However, the points b and D_b must be distinct since they are contained in a common triple in S .

- **The sets $\{A, a, D\}$, $\{B, b, D\}$ and $\{C, c, D\}$ induce Steiner triple systems isomorphic to S_9 .**

Assume first that D and every two points of S' induce a Steiner triple system isomorphic to S_9 . In particular, the points A, B and D induce such a Steiner triple system and thus $(A \oplus D) \oplus (B \oplus D) = D_A \oplus D_B$ is equal to $c \oplus D = D_C$; see Figure 9(a). Let $x = m \oplus D_A = D_m \oplus a$, $y = m \oplus D_B = D_m \oplus b$, $z = m \oplus D_C = D_m \oplus c$ and $z' = m \oplus D_c = D_m \oplus C$ (the points x, y, z and z' exist since the configurations are isomorphic to S_9). See Figure 9(b), (c) and (d).

Consider the Steiner triple system induced by the points D_m, a and b . If this Steiner triple system is isomorphic to S_7 , then $x \oplus y$ is the point c ; otherwise, it is isomorphic to S_9 and $x \oplus y = z$. Consider now the Steiner triple system induced by the points m, D_A and D_B . If it is isomorphic to S_7 , then $x \oplus y = D_A \oplus D_B = D_C$; otherwise, it is

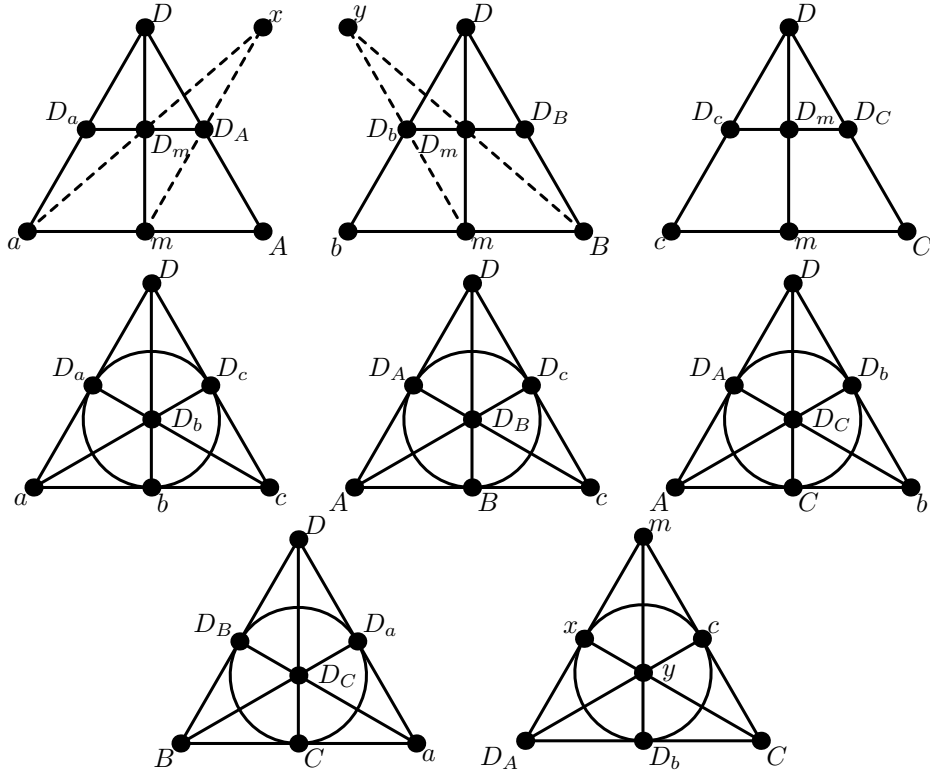


Figure 10: Configurations contained in S in case where all the triples $\{A, a, D\}$, $\{B, b, D\}$ and $\{C, c, D\}$ induce Steiner triple systems isomorphic to S_9 , but a, b and D induce a Steiner triple system isomorphic to S_7 .

isomorphic to S_9 and $x \oplus y$ is the point $z' = m \oplus D_c = D_m \oplus C$. We conclude that $x \oplus y$ is the same point as two of the points c, z, D_c and z' . However, this is impossible since these points are mutually distinct as they form a Steiner triple system isomorphic to S_9 . We conclude that S' contains two points that induce with D a Steiner triple system isomorphic to S_7 .

By symmetry, we can now assume that the points a, b and D induce a Steiner triple system isomorphic to S_7 , see Figure 10. In particular, $b = D_a \oplus D_c$. Consider the Steiner triple system induced by the points D_m, D_a and D_c . Since $D_m \oplus D_a = D_A$ and $D_m \oplus D_c = D_C$, the point $D_A \oplus D_C$ is either the point b (if the considered Steiner triple system

is isomorphic to S_7) or the point $D_m \oplus b$ (if it is isomorphic to S_9). By considering the Steiner triple system induced by the points D , A and C , we derive that the point $D_A \oplus D_C$ is either b or $D \oplus b$. The former holds if the induced Steiner triple system is isomorphic to S_7 , the latter if it is isomorphic to S_9 . Since the points b , $D_m \oplus b$ and $D \oplus b$ are distinct, the Steiner triple system induced by D , A and C must be isomorphic to S_7 . By symmetry, the Steiner triple systems induced by D , A and B , and D , B and C are also isomorphic to S_7 .

Let $x = a \oplus D_m = m \oplus D_A$ and $y = B \oplus D_m = m \oplus D_b$. Consider now the Steiner triple system induced by the points m , D_A and D_b . Since $D_A \oplus D_b = C$ (recall that the Steiner triple system induced by A , C and D is isomorphic to S_7), the point $x \oplus y$ is either C (if the induced system is isomorphic to S_7) or $m \oplus C = c$ (if the induced system is isomorphic to S_9). Similarly, by considering the Steiner triple system induced by D_m , a and B , we derive that $x \oplus y$ is either C or $D_m \oplus C$. Since the points C , $m \oplus C$ and $D_m \oplus C$ are distinct, both the Steiner triple system induced by m , D_A and D_b and one induced by D_m , a and B are isomorphic to S_7 and $x \oplus y = C$. Hence, $D_B = D_A \oplus c = y$ but the points y and D_B must be distinct since they are contained in the copy of S_9 induced by the points m , B and D .

We have shown that a non-projective Steiner triple system that is not a Hall triple system and such that every three independent points induce a Steiner triple system isomorphic to S_7 or S_9 cannot exist. The statement of the lemma now follows. \square

5 Characterizations of affine Steiner triple systems and Hall triple systems

Before we can state our characterization results, we have to show that every Steiner triple system containing C_A also contains one of the configurations C_S^1 and C_S^2 . We prove instead that it homomorphically contains C_S which is equivalent by Lemma 2.

Lemma 6. *Every Steiner triple system S containing the anti-mitre configuration C_A also homomorphically contains the squashed-square configuration C_S .*

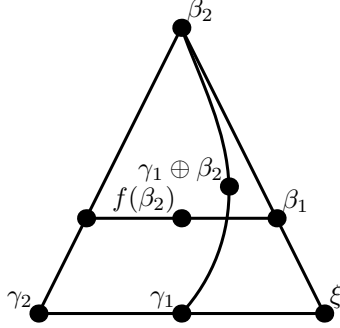


Figure 11: The notation used in the proof of Lemma 6.

Proof. Choose the points ξ , β_1 , β_2 , γ_1 and γ_2 to be the points of the anti-mitre configuration as depicted in Figure 11. Note that the five points are distinct and $\xi = \beta_1 \oplus \beta_2 = \gamma_1 \oplus \gamma_2$.

For a point z of a Steiner triple system S , let $f(z) = (z \oplus \gamma_2) \oplus \beta_1$ and $h(z) = (z \oplus \beta_2) \oplus \gamma_1$. Note that the functions f and h are not defined for all the points of S . More precisely, the function $f(z)$ is a bijection between its domain $D(f) = S \setminus \{\gamma_2, \gamma_2 \oplus \beta_1\}$ and its image set $R(f) = S \setminus \{\beta_1, \gamma_2 \oplus \beta_1\}$. Similarly, $h(z)$ is a bijection between $D(h) = S \setminus \{\beta_2, \beta_2 \oplus \gamma_1\}$ and $R(h) = S \setminus \{\gamma_1, \gamma_1 \oplus \beta_2\}$.

Observe that if there exists a point z of S such that both $f(z)$ and $h(z)$ are defined and $f(z) \neq h(z)$, we are able to construct the squashed-square configuration in S . Indeed, we set $x_0 = z$, $\alpha_1 = z \oplus \gamma_2$, $\delta_1 = z \oplus \beta_2$, $x_{\alpha\beta} = f(z) = \alpha_1 \oplus \beta_1 = (z \oplus \gamma_2) \oplus \beta_1$, and $x_{\gamma\delta} = h(z) = \delta_1 \oplus \gamma_1 = (z \oplus \beta_2) \oplus \gamma_1$; see Figure 4. Hence, in order to establish the statement of the lemma, it is enough to show that there exists a point z of S such that $f(z) \neq h(z)$.

Recall that f and h are defined on all the points of S except $\beta_2, \gamma_2, \beta_1 \oplus \gamma_2$ and $\beta_2 \oplus \gamma_1$. The points β_2 and γ_2 are distinct from the remaining exceptional points, however, the points $\beta_1 \oplus \gamma_2$ and $\beta_2 \oplus \gamma_1$ might be the same. Analogously, the set of possible common values of f and h are the points of S except for $\beta_1, \gamma_1, \beta_1 \oplus \gamma_2$ and $\beta_2 \oplus \gamma_1$. Again, these points are distinct with a possible exception of the pair of $\beta_1 \oplus \gamma_2$ and $\beta_2 \oplus \gamma_1$. Since the pairs of points that could be the same point are the same pairs both for the domains and image sets of f and h , it holds that $|D(f) \cap D(h)| = |R(f) \cap R(h)|$.

Assume to the contrary that there is no point z such that $z \in D(f) \cap D(h)$ and $f(z) \neq h(z)$. In particular, f and h restricted to $D(f) \cap D(h)$ are the same

bijjective mapping onto $R(f) \cap R(h)$. Therefore, the points of $D(f) \setminus D(h)$ are mapped by f to $R(f) \setminus R(h)$. We conclude that $f(\beta_2)$ is one of the points γ_1 and $\gamma_1 \oplus \beta_2$. However, $f(\beta_2)$ cannot be either of these two points; see Figure 11. \square

We can now state the theorem characterizing affine and Hall Steiner triple systems.

Theorem 7. *A Steiner triple system S is affine if and only if it contains neither of the configurations C_{16} , C_S^1 or C_S^2 . Moreover, if S is known to be non-projective, then S is affine if and only if it contains neither of the configurations C_S^1 and C_S^2 .*

Similarly, S is a Hall triple system if and only if it contains neither of the configurations C_{16} and C_A , and if S is known to be non-projective, then S is Hall if and only if it does not contain the configuration C_A .

Proof. It is easy to see that an affine Steiner triple system S cannot contain either of the configurations C_{16} , C_S^1 and C_S^2 . Suppose now that S is not affine. If S is projective, then it contains C_{16} . If S is a Hall triple system, then it contains C_S^1 or C_S^2 by Lemmas 2 and 3. Finally, if S is not projective and not a Hall triple system, then it contains C_A by Lemma 5, and hence it contains one of the configurations C_S^1 or C_S^2 by Lemmas 2 and 6.

Similarly, a Hall triple system S contains neither C_{16} nor C_A as neither of these two configurations is contained in S_9 . Analogously to the above argument, a projective Steiner triple system S contains the configuration C_{16} , and a non-projective Steiner triple system that is not a Hall triple system contains the configuration C_A by Lemma 5. \square

6 Preliminary results on colorings with points of Steiner triple systems

We now turn our attention to applying our characterization results to edge-colorings of cubic graphs. We start with recalling several results on colorings of cubic graphs with Steiner triple systems. As the first, a theorem on edge-colorings of bridgeless cubic graphs with the points of Steiner triple systems from [7] is stated and proved. We provide its proof though the main idea follows that of [7] because of several reasons, the most important being that the proof is later altered to obtain edge-colorings in more special scenarios

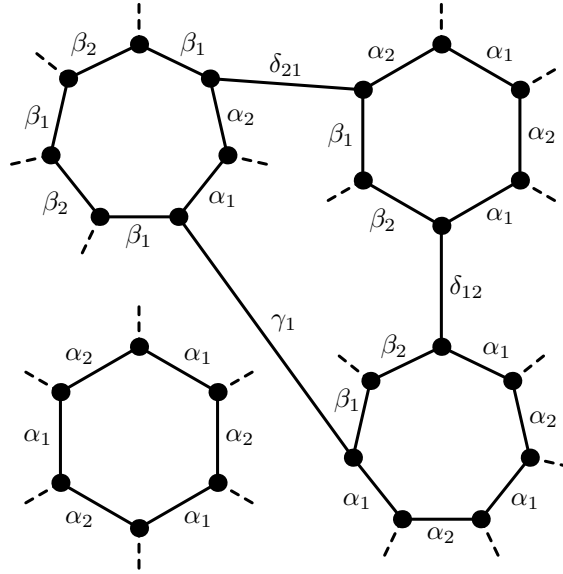


Figure 12: The coloring constructed in the proof of Theorem 8. The edges of $M \setminus (T_1 \cup T_2)$ are drawn as dashed and colored with the point ξ .

and we want to avoid extensive referring to a different paper. Another reason is that we want to give the proof using our notation. Given a subgraph C of a graph G , let G/C be the graph obtained by contracting the components of C to single vertices, and removing the loops that may arise (but not the parallel edges).

Theorem 8 (Holroyd and Škoviera [7]). *Let S be a non-trivial Steiner triple system. Every bridgeless cubic graph is S -edge-colorable. Moreover, for every edge e of G and every point ξ of S , there exists an S -edge-coloring that assigns ξ to e .*

Proof. It can be shown using standard graph theory arguments that G contains a perfect matching M with the following properties (see [8, 9] for instance): M contains the edge e and the graph $H = G/C$, where C is the complement of M in G , contains two edge-disjoint spanning forests T_1 and T_2 , $e \notin T_1 \cup T_2$, such that the degree of a vertex v is odd in T_i , $i = 1, 2$, if and only if the degree of v in H is odd. Such spanning forests are called *parity forests*.

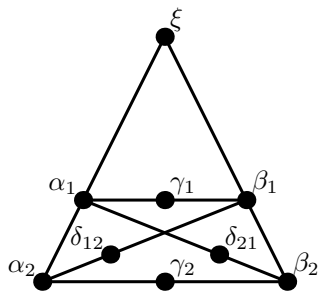


Figure 13: The notation used in the proof of Theorem 8.

Choose an arbitrary point α_1 of S distinct from ξ and set $\alpha_2 = \xi \oplus \alpha_1$. Let β_1 be a point of S distinct from ξ , α_1 and α_2 and let $\beta_2 = \xi \oplus \beta_1$. Further, let $\gamma_i = \alpha_i \oplus \beta_i$ for $i = 1, 2$. Finally, let $\delta_{12} = \alpha_2 \oplus \beta_1$ and $\delta_{21} = \alpha_1 \oplus \beta_2$; see Figure 13.

If all the cycles of C were even, we would color the edges of M with ξ and the edges of the cycles with α_1 and α_2 alternately. This would give us the desired coloring of the edges of G . However, some cycles of C could be odd. We cope with this in the rest of the proof.

The edges of cycles will be colored with α 's and β 's in such a way that the indices of the colors alternate precisely at vertices not incident with the edges of T_1 . Once we choose which edges of a cycle C_1 of C are colored with α_1 or β_1 and which with α_2 or β_2 , the points assigned to the edges of T_1 incident with C_1 are determined to be either γ_1 or γ_2 depending on the colors of the two edges incident with that edge of T_1 . The choice of a coloring of a single cycle corresponding to a vertex of a component of T_1 determines the colorings of the edges of all cycles corresponding to the vertices of the same component of T_1 . Since T_1 is acyclic and each cycle is incident with the number of edges of T_1 matching its parity, the edges of T_1 can be colored with γ_1 and γ_2 in such a way that the coloring of T_1 can be extended to all cycles.

Similarly, we can partition the edges of C into two classes such that the edges of one of the classes will be colored with α_1 or β_2 , and the edges of the other class with α_2 or β_1 . The classes alternate at vertices not incident with an edge of T_2 and the edges of T_2 get the colors δ_{12} and δ_{21} .

In the just described way, we have defined colorings of the edges of T_1 and T_2 . The edges of M not contained in T_1 or T_2 are colored by ξ . As discussed

above, the coloring of the edges of M extends to the edges of C . Indeed, the colors of the edges of T_1 determine the indices and those of T_2 then completely fix the colors assigned to the edges of C . Since $e \in M \setminus (T_1 \cup T_2)$, the color of e is ξ as desired. The proof of the lemma is now completed. \square

Note that in addition to prescribing the color of e to be ξ , we can also assume in the proof of Theorem 8 that the colors of the edges of the even cycles corresponding to vertices that are isolated both in T_1 and T_2 are colored with α_1 and α_2 alternately, and fix a coloring of one odd cycle.

We now sketch an alternative proof of the following result of Pál and Škoviera [10]—we focus on the aspects that are different and used in our further arguments. The proof was obtained during discussions of Zdeněk Dvořák and the first author.

Theorem 9 (Pál and Škoviera [10]). *Every cubic graph with no bipartite end is $AG(d, 3)$ -edge-colorable for all $d \geq 3$.*

The graph is first split into blocks with half-edges corresponding to bridges incident with the blocks. We next construct an edge-coloring of each block. It is required that the points assigned to each triple of edges sharing the same vertex form a triple in the system. In particular, the points assigned to a half-edge and the two edges incident with it form a triple. As stated in the next lemma, it is enough to be able to construct edge-colorings of non-bipartite ends and bridgeless cubic graphs since the half-edges of non-trivial blocks incident with more bridges can be merged to obtain graphs only of these two kinds.

Lemma 10. *Let H be a non-trivial block of a cubic graph incident with at least two half-edges. If H is incident with an odd number of half-edges and H is not a triangle with three half-edges, then the half-edges can be identified in such a way that the resulting graph is a non-bipartite end. On the other hand, if H is incident with an even number of half-edges, then the half-edges of H can be identified in such a way that the resulting graph (after a possible successive removal of pairs of parallel edges) is either a simple bridgeless cubic graph or a graph formed by a triple of parallel edges.*

Proof. If H is incident with four or more half-edges, then H contains two half-edges f_1 and f_2 which are not incident with adjacent vertices. We identify the half-edges f_1 and f_2 and obtain a block with less half-edges and without

parallel edges that also satisfies the assumption of the lemma. Hence, we assume in the rest that the block is incident with two or three half-edges.

If H is incident with two half-edges, we identify the two half-edges and obtain a bridgeless cubic graph H' which need not be simple. We next remove pairs of parallel edges as we describe in Introduction: remove the pair of parallel edges and identify the two edges incident with the pair of parallel edges that remain in the graph. Note that the graph is kept being bridgeless and cubic in this way and thus we cannot obtain a loop. Hence, we either end with a simple bridgeless cubic graph or a triple of parallel edges as claimed in the statement of the lemma.

The case where H is incident with three half-edges is more involved. We distinguish two cases based on whether or not the vertices of H can be colored with two colors. If the vertices can be colored with two colors, then identify two half-edges incident with vertices of the same color. This does not create a pair of parallel edges. In addition, the resulting graph is not a bipartite end since we have just created an odd cycle.

If the vertices of H cannot be 2-colored, then identifying any pair of half-edges does not create a bipartite end. Hence, we have only to avoid creating a pair of parallel edges, i.e., we have to identify half-edges incident with non-adjacent vertices. This is possible unless H is a triangle with incident three half-edges. \square

Every bridgeless cubic graph as well as a trivial block or a block formed by a triangle with three incident half-edges is $\text{AG}(d, 3)$ -edge-colorable [7]. Therefore, we only have to establish that each non-bipartite end is $\text{AG}(d, 3)$ -edge-colorable for all $d \geq 3$ to finish the proof of Theorem 9. We next show that if the non-bipartite end is 3-edge-colorable, then it is indeed $\text{AG}(d, 3)$ -edge-colorable for every $d \geq 2$.

Lemma 11. *Let S be a non-trivial affine Steiner triple system. Every 3-edge-colorable non-bipartite end G_0 is S -edge-colorable.*

Proof. Let S be an affine Steiner triple system $\text{AG}(d, 3)$, $d \geq 2$. The points of S are d -dimensional vectors (x_1, \dots, x_d) with $x_i \in \{0, 1, 2\}$. Let G be the graph obtained from G_0 by suppressing the vertex incident with the half-edge and let e be the new edge of G . For the rest of the proof, we fix a 3-edge-coloring of G .

We claim that G contains an odd cycle C_0 passing through the edge e . Since G is not bipartite, it contains an odd cycle C . If $e \in C_0$, the claim

holds. Assume that $e \notin C_0$. Since G is bridgeless, there exist two edge-disjoint paths in G from the end-vertices of e to C . The two paths combine with one of the two parts of C delimited by the final vertices of the paths to an odd cycle C_0 containing the edge e .

We are now ready to define the S -edge-coloring of G_0 . The first coordinate x_1 is equal to 0, 1 or 2 depending on the color of the edge of G in the fixed coloring. Note that the first coordinate of every two incident edges except for the two edges incident with the half-edge are distinct. The second coordinate x_2 is equal to 0 for all the edges not contained in C_0 . For the other edges which form an even cycle in G_0 , the second coordinate alternates between 1 and 2. The remaining coordinates x_i , $i > 2$, are equal to 0. It is easy to verify that the defined coloring is an S -edge-coloring of G_0 . \square

The proof that each non-3-edge-colorable (and thus non-bipartite) end is $AG(d, 3)$ -edge-colorable if $d \geq 3$, is obtained by combining arguments used in the proofs of Theorem 8 and Lemma 11. The first two coordinates are used to mimic the edge-coloring from the proof of Theorem 8 and the third coordinate to distinguish the colors assigned to the edges incident with the half-edge (in the same way as the second coordinate in the proof of Lemma 11). Since we do not use Theorem 9 in our further considerations and only use Lemmas 10 and 11, we leave the details missing to complete the proof of Theorem 9 to the reader.

7 Non-3-edge-colorable ends

By Lemma 10, the problem of an edge-coloring of a cubic graph can be decomposed into several problems dealing with edge-colorings of ends. In this section, we consider ends that are not 3-edge-colorable.

Lemma 12. *Let S be a Steiner triple system containing the configuration C_{14} . Every non-3-edge-colorable end G_0 is S -edge-colorable.*

Proof. We alter the proof of Theorem 8. The points of C_{14} are ξ , α_i , β_i and γ_i as in Figure 1(a). Note that this is consistent with the notation used in the proof of Theorem 8.

Let e_1 and e_2 be the two edges incident with the half-edge and G be the bridgeless cubic graph obtained by suppressing the vertex incident with the half-edge. Let e be the resulting edge of G . As in Theorem 8, we consider

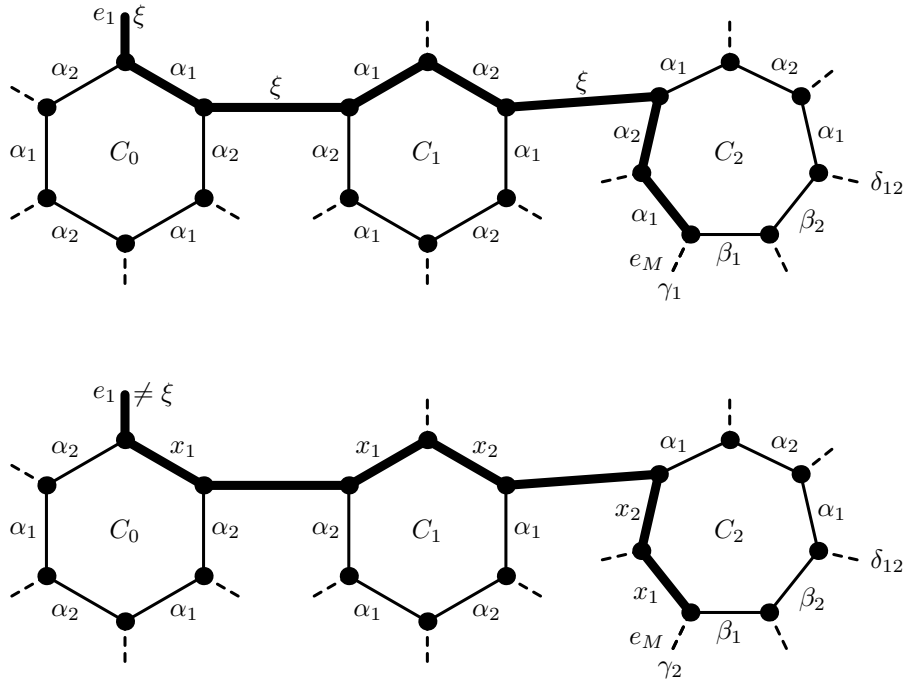


Figure 14: The modification of the coloring performed in the proof of Lemma 12—the original coloring is in the top and the modified in the bottom of the figure. The edges of the path P are drawn solid bold.

a perfect matching M , $e \in M$, and two disjoint parity forests T_1 and T_2 of G/C where C is the complement of M and $e \notin T_1 \cup T_2$. Let v_0 be the vertex of G/C corresponding to a cycle incident with e_1 .

Since the end is not 3-edge-colorable, G/C contains a vertex of odd degree. Hence, both T_1 and T_2 contain some edges. Let $v_0 \cdots v_k$ be a shortest path in G/C from the vertex v_0 to a vertex v_k that is not isolated in T_1 or T_2 . Note that k may be 0. Further, let C_i be the cycle of C corresponding to the vertex v_i , $i = 0, \dots, k$, and let P be the path in G_0 comprised of the edge e_1 , the edges corresponding to the path $v_0 \cdots v_k$ and parts of the cycles C_0, \dots, C_k . By symmetry, we can assume that e_2 does not belong to P , see Figure 14. The last vertex of P is the only vertex of P incident with an edge contained in $T_1 \cup T_2$.

Next, we modify the coloring obtained in the proof of Theorem 8. As mentioned after its proof, we can assume that the edges of $P \cap C$ are colored

with α_1 and α_2 only. In addition, we can assume that the colors of edges of $P \cap C$ incident with the same edge of $P \cap M$ are the same, i.e., they both are either α_1 or α_2 , the last edge of P is colored with α_1 and the edge e_M of M incident with the last vertex of P is contained in T_1 (see the figure). In particular, the color of e_M is γ_1 . Note that all the edges of $P \cap M$ are colored with ξ .

Let x_1 be the point $\beta_1 \oplus \gamma_2$. Note that x_1 is distinct from the points ξ , α_1 and α_2 . Further, let $x_2 = \xi \oplus x_1$. Analogously, x_2 is different from α_1 and α_2 . Note that $\alpha_2 + x_i \neq \xi$ for each $i \in \{1, 2\}$.

We now alter the constructed coloring. Recolor the edge e_M to γ_2 and swap the indices of the colors of the edges of the subtree of T_1 separated by e_M from v_k , i.e., the edges of the subtree colored with γ_1 are now colored with γ_2 and vice versa. This results in a change of the coloring of the edges of C contained in the cycles incident with edges of swapped colors. By the choice of the path $v_0 \cdots v_k$, the colors of all the edges of P as well as edges incident with them except for the edge e_M have been preserved.

We now modify the coloring of the edges of P in such a way that the obtained coloring is an S -edge-coloring of G_0 . The colors of the edges of $P \cap C$ that are originally colored with α_i are changed to x_i both for $i = 1$ and $i = 2$. Consider now an edge $f \in P \cap M$. Note that both the ends of f are either incident with edges colored α_1 and x_2 , or with edges colored α_2 and x_1 . Hence, we can extend the coloring to the edges of $P \cap M$. Since the color of e_1 is not equal to ξ , and the color of e_2 is ξ , the coloring can also be extended to the half-edge of G_0 which is incident with e_1 and e_2 . This finishes the proof of the lemma. \square

8 3-edge-colorable ends

In Section 7, we constructed colorings of non-3-edge-colorable ends. It remains to consider 3-edge-colorable ends. It seems that the core of the problem lies in hamiltonian ends. More precisely, we first construct the desired colorings for hamiltonian ends and we later show how to reduce the problem of coloring general 3-edge-colorable ends to hamiltonian ones. The first case we consider are hamiltonian non-bipartite ends.

Lemma 13. *Let S be a Steiner triple system containing the configuration C_{14} . Every hamiltonian non-bipartite end G_0 is S -edge-colorable. More-*

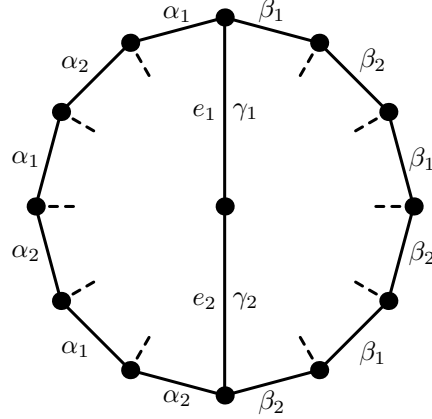


Figure 15: The coloring of G_0 constructed in the proof of Lemma 13 in the case where the cycle C_e is odd in G . The dashed chords are labeled with ξ .

over, there exists an S -edge-coloring such that the edges not contained in the Hamilton cycle receive at most three distinct colors.

Proof. Let G be the graph obtained from G_0 by suppressing the vertex incident with the half-edge, e the resulting edge of G , and e_1 and e_2 the two edges of G_0 incident with the half-edge. Further, let C_H be the Hamilton cycle with $e \notin C_H$ and for every chord f of C_H , let C_f be one of the cycles formed by f and a part of the cycle C_H . Since the cycles C_H and C_f form a base of the cycle space of G and G is not bipartite, one of these cycles is odd. Since G is cubic, the length of C_H is even and thus one of the cycles C_f is odd.

We first consider the case that the cycle C_e is odd (in the graph G). The edges e_1 and e_2 are colored with γ_1 and γ_2 , the other chords of C_H are colored with ξ . The edges of one of the parts of C_H delimited by e are colored with α_1 and α_2 and the edges of the other part with β_1 and β_2 (see Figure 15). Let us remind that the points of C_{14} are ξ, α_i, β_i and γ_i as in Figure 1(a).

In the rest of the proof, we assume that the cycle C_e is even and consider a cycle $C_f, f \neq e$, that is odd. Before we proceed further, let us introduce some additional notation: α'_1 is the point $\alpha_2 \oplus \gamma_1$, α'_2 is $\xi \oplus \alpha'_1$, and ξ' is $\alpha'_2 \oplus \beta_2$. Since $\alpha'_1 \neq \xi$, the point α'_2 is well-defined. Moreover $\alpha'_2 \neq \beta_2$, i.e., the point ξ' is also well-defined.

We now distinguish two cases based on whether the chords e and f cross. If the chords e and f cross (see Figure 16(a)), color f with γ_1 and one of

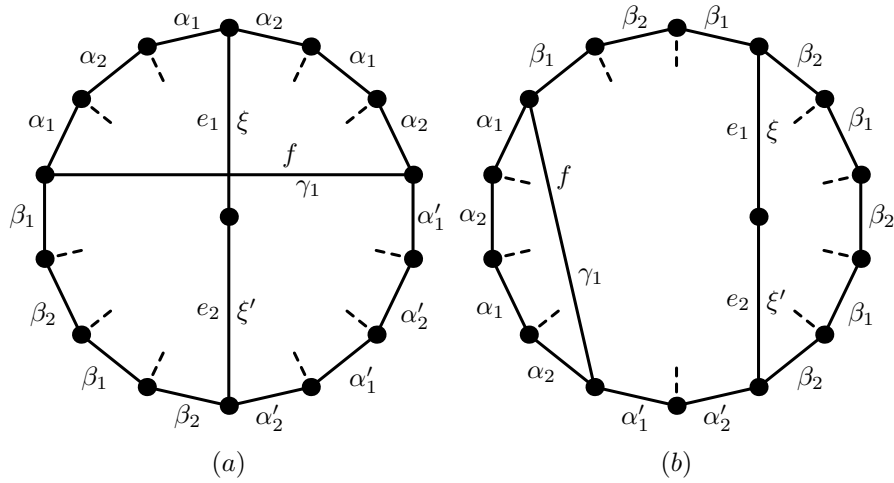


Figure 16: The colorings of G_0 constructed in the proof of Lemma 13 in the case where the cycle C_e is even and (a) the chords e and f cross, (b) the chords e and f do not cross. The dashed chords are labeled with ξ .

the parts of C_H delimited by f , say one incident with e_1 , with α_1 and α_2 alternately. The other part of C_H is split by e_2 into two parts: the edges of one of the parts are colored with β_1 and β_2 alternately and the edges of the other with α'_1 and α'_2 alternately. Finally, the edges e_1 and e_2 are colored with ξ and ξ' , and the remaining chords of C_H are colored with ξ . It is straightforward to verify that the coloring is an S -edge-coloring. Since $\xi \neq \xi'$, the coloring can be extended to the half-edge.

The final case to consider is that the chords e and f do not cross. By the symmetry, we can assume that the part of C_H delimited by e_1 and f is odd and the part delimited by e_2 and f is even; see Figure 16(b). The edges of the part of C_H between f and e_1 , and e_1 and e_2 , are colored with β_1 and β_2 alternately. The edge f is assigned γ_1 and the edges of the part of C_H delimited by f are assigned α_1 and α_2 alternately. The remaining edges of C_H are then colored with α'_1 and α'_2 . Finally, the edge e_2 is colored with ξ' and the remaining chords of C_H with ξ . Since $\xi \neq \xi'$, this coloring can also be extended to the half-edge.

Note that, regardless whether the cycle C_e is odd or even, there are three distinct points assigned to the edges not contained in the Hamilton cycle, namely, the points γ_1, ξ and ξ' . \square

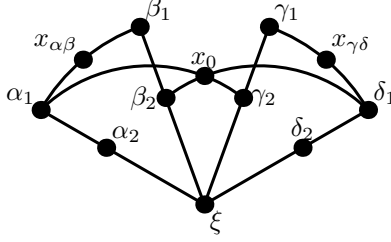


Figure 17: The squashed-square configuration C_S enhanced by two new points $\alpha_2 = \xi \oplus \alpha_1$ and $\delta_2 = \xi \oplus \delta_1$. Note that it is required that $x_{\alpha\beta} \neq x_{\gamma\delta}$ but the other pairs of points can coincide.

It remains to consider hamiltonian bipartite ends. This is the point where we will utilize our characterization results since such ends cannot be edge-colored by affine Steiner triple systems.

Lemma 14. *Let S be a Steiner triple system homomorphically containing the squashed-square configuration C_S . Every hamiltonian bipartite end G_0 is S -edge-colorable. Moreover, there exists an S -edge-coloring such that the edges not contained in the Hamilton cycle receive at most five distinct colors.*

Proof. Let us enhance the squashed-square configuration C_S by introducing two new points $\alpha_2 = \xi \oplus \alpha_1$ and $\delta_2 = \xi \oplus \delta_1$; see Figure 17. Let G be the graph obtained from G_0 by suppressing the vertex incident with the half-edge, e the resulting edge of G , and e_1 and e_2 the two edges of G_0 incident with the half-edge. Further, let C_H be the Hamilton cycle of G with $e \notin C_H$.

Assume first that G contains a chord f that crosses e as depicted in Figure 18. The edge e_1 is colored with $x_{\alpha\beta}$, e_2 with $x_{\gamma\delta}$, and f with x_0 . The other chords of C_H are colored with ξ . The edges of the parts of C_H delimited by e and f are colored with α_1 and α_2 , β_1 and β_2 , γ_1 and γ_2 , and δ_1 and δ_2 , each part with one of the pairs of the colors alternately. Since $x_{\alpha\beta} \neq x_{\gamma\delta}$, the coloring can be extended to the half-edge. Note that only the points ξ , x_0 , $x_{\alpha\beta}$ and $x_{\gamma\delta}$ are assigned to the edges not contained in the Hamilton cycle.

A more involved case is when no chord of C_H crosses e . Since G has no parallel edges (with a possible exception of e), it contains a pair of crossing chords. Each pair of crossing chords split C_H into four parts, out of which one is incident with both the end-vertices of e . Choose among all pairs of chords f_1 and f_2 the one with distance between the end-vertices of f_1 and f_2

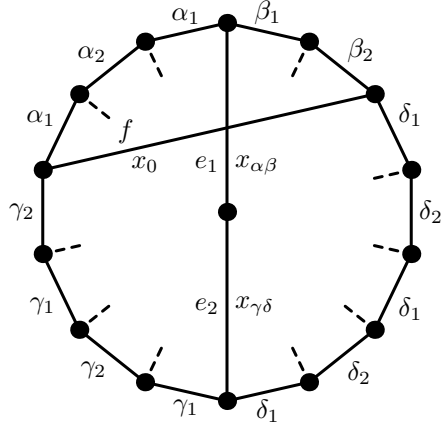


Figure 18: The coloring of G_0 constructed in the proof of Lemma 14 in the case where there is a chord crossing e . The dashed chords are labeled with ξ .

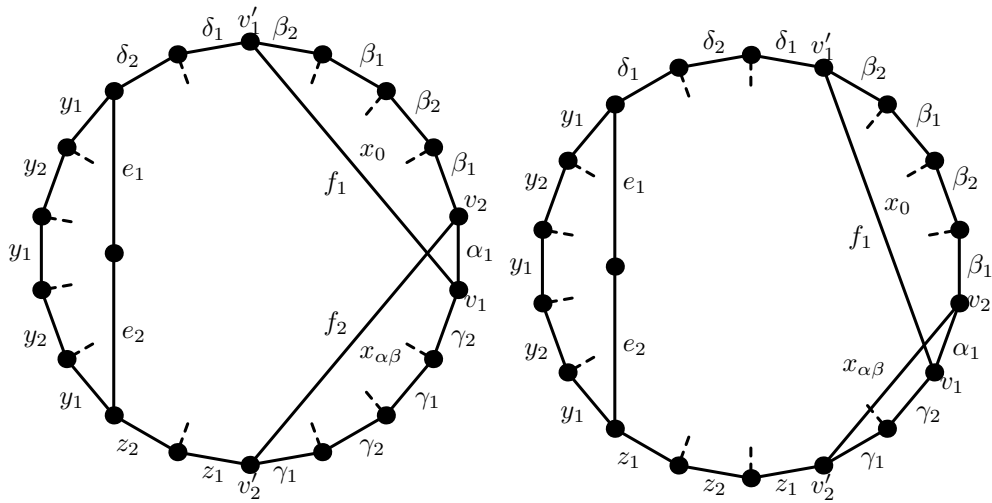


Figure 19: The colorings of G_0 constructed in the proof of Lemma 14 in the case where there is no chord crossing e . The dashed chords are labeled with ξ .

delimiting the part opposite to the part incident with e the smallest possible. It is not hard to show that this distance must be equal to one, otherwise, there would exist a pair of crossing chords with closer end-vertices. Let v_1 and v_2 be the end-vertices of f_1 and f_2 that are adjacent and v'_1 and v'_2 the other end-vertices of f_1 and f_2 .

Before we proceed further, we show that it can be assumed that $x_{\alpha\beta} \neq \gamma_1$ or $x_{\gamma\delta} \neq \beta_1$ (note that the two inequalities are symmetric). If $x_{\alpha\beta} = \gamma_1$ and $x_{\gamma\delta} = \beta_1$, then $\alpha_1 = \delta_1$; see Figure 17. Consequently, $\beta_2 = \gamma_2$ and $\beta_1 = \gamma_1$. However, this implies $x_{\alpha\beta} = x_{\gamma\delta}$ which is inconsistent with the definition of the configuration C_S . Hence, we can assume that $x_{\alpha\beta} \neq \gamma_1$ in the rest of the proof. Since $x_{\alpha\beta} \neq \gamma_1$, there exists a point z_1 that forms a triple with $x_{\alpha\beta}$ and γ_1 . Observe that $z_1 \neq \xi$ (otherwise, $x_{\alpha\beta}$ would be equal to γ_2 , x_0 would be β_1 and ξ would be δ_1 which is impossible). Consequently, there exists a point $z_2 = \xi \oplus z_1$.

We are now ready to color the edges of G . The edge v_1v_2 is colored with α_1 , the edge f_1 with x_0 and the edge f_2 with $x_{\alpha\beta}$. The chords of C_H distinct from e_1 , e_2 , f_1 and f_2 are colored with ξ . The edges of the part of C_H delimited by v_1 and v'_2 are colored with γ_1 and γ_2 alternately and the edges of the part delimited by v_2 and v'_1 are colored with β_1 and β_2 as in Figure 19. This coloring switches at the vertex incident with f_1 to an alternating coloring with δ_1 and δ_2 until it hits the end-vertex of the edge e_1 . The edges of C_H between the end-vertices of e_2 and f_2 are colored with z_1 and z_2 alternately; see Figure 19.

It remains to color the edges of the part of C_H delimited by e and the edges e_1 and e_2 themselves. The colored edge incident with e_1 is colored with δ_k and the colored edge incident with e_2 is colored with z_k (note that the indices of the two colors are the same by the parity constraints). We assert that $\delta_k \neq z_k$: if $z_1 = \delta_1$, then $x_{\alpha\beta} = x_{\gamma\delta}$ which is impossible. If $z_2 = \delta_2$, then $z_1 = \delta_1$ which we have just excluded.

Choose arbitrary a point y_1 of S that is distinct from ξ , δ_k and z_k , and let $y_2 = \xi \oplus y_1$. The remaining edges of H_C are colored with y_1 and y_2 alternately in such a way that the edges e_1 and e_2 are incident with edges colored with y_1 . Since $y_1 \notin \{z_k, \delta_k\}$, the coloring can be extended to e_1 and e_2 . Moreover, since $z_k \neq \delta_k$, the colors of e_1 and e_2 are distinct. Hence, the coloring can also be extended to the half-edge.

It remains to verify that there are at most five points used to color the edges not contained in the Hamilton cycle: indeed, only the points ξ , x_0 , $x_{\alpha\beta}$ and the points assigned to e_1 and e_2 are such points. The proof of the lemma

is now finished. □

We have constructed colorings of hamiltonian ends. A 3-edge-colorable end does not need to be hamiltonian in general but we can reduce the problem to hamiltonian ends as described in the next lemma.

Lemma 15. *Let S be a Steiner triple system containing the configuration C_{14} and the squashed-square configuration C_S . Every 3-edge-colorable end G_0 is S -edge-colorable.*

Proof. Let G be the graph obtained by suppressing the vertex u incident with the half-edge and $e = v_0v_1$ the resulting edge. Fix a coloring of the edges of G with three colors, say red, green and blue, such that the edge e is red and the cycle formed by green and blue edges that contains v_0 is the longest possible.

Let w_1, \dots, w_k be the vertices of the cycle formed by green and blue edges that contains the vertex v_0 and assume that $w_1 = v_0$. We construct an auxiliary end H_0 with the vertices w_0, \dots, w_k where w_0 is a new vertex which will be incident with the half-edge of H_0 . The cycle $w_1 \cdots w_k$ is contained in H_0 . In addition, the vertices w_i and w_j are joined in H_0 by an edge e_{ij} if G contains a path P_{ij} formed by red and blue edges such that w_i and w_j are the only vertices of P_{ij} contained in the cycle $w_1 \cdots w_k$. Note that for each vertex w_i , there exists a unique vertex w_j with this property. The chord incident with w_1 is replaced by a path containing the vertex w_0 . Observe that the resulting graph H_0 is a hamiltonian end. In addition, H_0 has no parallel edges: if two vertices w_i and w_j adjacent in the cycle were joined by a chord, then we could assume by the symmetry that the edge w_iw_j of the cycle is blue and switch the red and blue colors on the cycle $P_{ij} \cup \{w_iw_j\}$ thereby obtaining a longer green-blue cycle with v_0 . This would contradict our choice of the 3-edge-coloring.

By Lemma 13 or 14 (depending on whether H_0 is bipartite), H_0 has an S -edge-coloring such that at most five distinct points of S are used to color the chords of the Hamilton cycle of H_0 . Choose a point ξ_0 of S distinct from the five points used on edges not contained in the Hamilton cycle. In addition, choose another point α_0 distinct from ξ_0 . We now construct an S -edge-coloring of the edges of G_0 . The edges of the cycle $w_1 \cdots w_k$ keep their colors. The red edges of the path P_{ij} get the color of the edge e_{ij} ; the edge w_1u gets the color of w_0w_1 , and the red edges on the path from w_1 as well as the edge uv_1 get the color of the other edge incident with w_0 . The

remaining red edges of G_0 are colored with α_0 . The green edges of G_0 not contained in the cycle $w_1 \cdots w_k$ are colored with ξ_0 .

The only edges that are not yet colored are blue edges not contained in the cycle $w_1 \cdots w_k$. Now observe that each end-vertex of every uncolored blue edge is incident with two edges colored with the same pair of points of S (one of these two colors being ξ_0). Hence, the coloring can be extended to all the edges of G_0 . This finishes the proof of the lemma. \square

9 Characterization of edge-colorability of cubic graphs

In Sections 7 and 8, we constructed S -edge-colorings of ends of cubic graphs. It remains to combine these colorings to a coloring of the whole cubic graph.

Theorem 16. *Let G be a cubic graph and S a non-trivial point-transitive Steiner triple system.*

- *If S is projective, then G is S -edge-colorable if and only if G is bridgeless.*
- *If S is affine, then G is S -edge-colorable if and only if G has no bipartite end.*
- *If S is neither projective nor affine, then G is always S -edge-colorable.*

Proof. Fix a cubic graph G and a non-trivial point-transitive Steiner triple system S . If S is projective, then G is S -edge-colorable if and only if G is bridgeless [7].

Next, we assume S is affine. If G has a bipartite end, then G is not S -edge-colorable [7]. Hence, assume G has no bipartite ends. If G is bridgeless, G is S -edge-colorable since all bridgeless cubic graphs are edge-colorable by all non-trivial Steiner triple systems; see Theorem 8. Hence, we also assume G has one or more bridges.

Split now the graph G along its bridges into several blocks. We now color each block with its incident half-edges. Since S is affine, it contains the configuration C_{14} . Hence, all the ends can be S -edge-colored either by Lemma 11 or by Lemma 12. Let us now consider a block incident with two or more half-edges. The trivial blocks and the blocks formed by a triangle with

three half-edges are clearly S -edge-colorable. By Lemma 10, the half-edges of the remaining blocks of G can be identified in such a way that the resulting graph (after a possible removal of parallel edges) is a bridgeless cubic graph, a triple edge or a non-bipartite end. All such graphs are S -edge-colorable as argued before. Since the obtained S -edge-coloring can be extended to the removed parallel edges, the original block of G is also S -edge-colorable.

It remains to combine the colorings of the blocks. After contracting the blocks of G into single vertices, the graph G becomes a tree. We further refer to the vertices as nodes in order to distinguish them from the vertices of G . Root this tree at any of its nodes. We fix the S -edge-colorings of the blocks from the root of the tree to its leaves. The block corresponding to the root keeps its original coloring. Since S is point-transitive, we can permute the colorings of the blocks corresponding to the nodes adjacent to the root (its children) in such a way that they match on the half-edges. Next, we permute the edge-colorings of the blocks corresponding to the grand-children in such a way that they match the colors of edges leading from the blocks corresponding to the children. We proceed in this way until we obtain an S -edge-coloring of the entire graph G .

It remains to consider the case where S is neither projective nor affine. By Theorems 1 and 7, and Lemma 2, we deduce that S contains the configuration C_{14} as well as it homomorphically contains the squashed-square configuration C_S . If G is bridgeless, G is S -edge-colorable by Theorem 8. Otherwise, we also split G along its bridges to blocks. The ends can be S -edge-colored by Lemmas 12 and 15. The trivial blocks and the blocks formed by triangles with three half-edges are S -edge-colorable from trivial reasons. The half-edges of the remaining blocks can be identified to get bridgeless graphs and (non-bipartite) ends. Hence, such blocks are also S -edge-colorable. The obtained colorings of the blocks of G can be combined to an S -edge-coloring of the whole graph G in the same way as in the case of affine Steiner triple systems. \square

As a corollary of Theorem 16, we derive the conjecture of Holroyd and Škoviča (Conjecture 1) for point-transitive Steiner triple systems.

Corollary 17. *Let G be a cubic graph and S a non-projective (and thus non-trivial) point-transitive Steiner triple system. If G has no bipartite end or S is not affine, then G is S -edge-colorable.*

10 Concluding remarks

In the first part of the paper, we have characterized several important classes of Steiner triple systems in terms of forbidden subconfigurations: we have shown that a Steiner triple system is affine if and only if it contains neither of the configurations C_{16} , C_S^1 or C_S^2 , and S is a Hall triple system if and only if it contains neither the configuration C_{16} nor C_A . It seems to be interesting to provide such characterizations of other important classes of Steiner triple systems.

Let us now turn our attention to edge-colorings of cubic graphs with elements of Steiner triple systems. Conjecture 1 is now proven for affine Steiner triple systems since all affine Steiner triple systems are point-transitive. Hence, it is only open whether every non-projective non-affine Steiner triple system that is not point-transitive is universal. The smallest such Steiner triple system has 13-vertices; let S'_{13} be this Steiner triple system. Note that there are only two Steiner triple systems with 13 vertices, namely the point-transitive system S_{13} mentioned in Section 1, and the system S'_{13} .

Along the lines of the proof of Theorem 16, we tried to establish that S'_{13} is also universal. First we identified several configurations such that if all of them are present in S'_{13} , all the ends can be colored. As in the proof of the lemmas in Sections 7 and 8, several cases based on whether the end is 3-colorable, bipartite, etc., need to be considered. Next, we prepared a computer program to check the presence of these configurations in S'_{13} with the additional requirement that one of their points, the one to be assigned to the half-edge, is a prescribed point of S'_{13} . In this way, the presence of all the needed configurations in S'_{13} with the special point being any of the points of S'_{13} was established.

Based on this, we concluded that each block of every cubic graph can be S'_{13} -edge-colored if one of the half-edges incident with it is precolored with a point of S'_{13} . Hence, the system S'_{13} is universal. We believe that an analogous argument can be used to establish that other small non-point-transitive Steiner triple systems are universal but we did not yet manage to develop any theoretical background that would give us any hope of extending our results to Steiner triple systems that need not be point-transitive.

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