

Clustered independence and bounded treewidth

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Abstract

A set $S \subseteq V$ of vertices of a graph G is a c -clustered set if it induces a subgraph with components of order at most c each, and $\alpha_c(G)$ denotes the size of a largest c -clustered set. For any graph G on n vertices and treewidth k , we show that $\alpha_c(G) \geq \frac{c}{c+k+1}n$, which improves a result of Wood [arXiv:2208.10074, August 2022], while we construct n -vertex graphs G of treewidth k with $\alpha_c(G) \leq \frac{c}{c+k}n$. In the case $c \leq 2$ or $k = 1$ we prove the better lower bound $\alpha_c(G) \geq \frac{c}{c+k}n$, which settles a conjecture of Chappell and Pelsmayer [Electron. J. Comb., 2013] and is best-possible. Finally, in the case $c = 3$ and $k = 2$, we show $\alpha_c(G) \geq \frac{5}{9}n$ and which is best-possible.

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1 Introduction

Let $G = (V, E)$ be a graph and c a positive integer. We call a subset $S \subseteq V$ of vertices of G a c -clustered set if every connected component of the subgraph $G[S]$ of G induced by S has at most c vertices. We define the c -clustered independence number $\alpha_c(G)$ of G as the maximum size of a c -clustered set in G . In particular, the 1-clustered sets of G are exactly the independent sets of G and $\alpha_1(G)$ equals the independence number $\alpha(G)$. On the other hand, for each 2-clustered set S of G the subgraph $G[S]$ is a collection of vertices and edges in G with no edge of G between these components, and $\alpha_2(G)$ is the largest number of vertices in G inducing only isolated vertices and edges.

In the literature, c -clustered sets appear primarily as the color classes of c -clustered colorings. A t -coloring $\phi: V \rightarrow [t]$ of the vertices of a graph $G = (V, E)$ is a c -clustered coloring if there is no monochromatic connected subgraph on more than c vertices in G . In other words, each color class $\phi^{-1}(i)$, $i = 1, \dots, t$, is a c -clustered set. The c -clustered chromatic number $\chi_c(G)$ is then the minimum t for which G admits a c -clustered t -coloring. So, for example, $\chi_1(G)$ is equal to the classical chromatic number $\chi(G)$, while $\chi_2(G)$ is

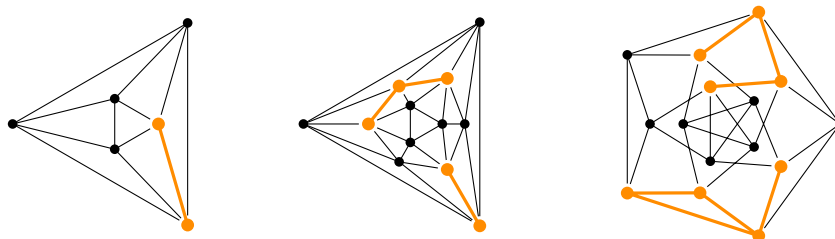
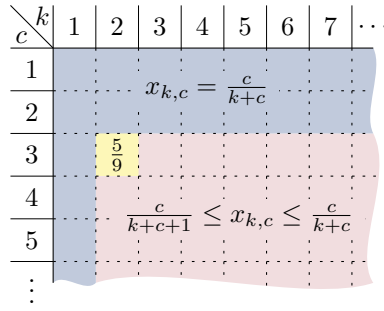


Figure 1 Examples of a 2-clustered set (left), a 3-clustered set (middle), and a 4-clustered set (right).



■ **Figure 2** Illustration of the bounds on $x_{k,c} = \liminf\{\alpha_c(G)/|V(G)| : \text{tw}(G) = k\}$ in Theorem 1.

the smallest number of 2-clustered sets into which the vertex set $V(G)$ can be partitioned. Clearly, for any $c \geq 1$ and any graph G we have

$$\alpha_c(G) \geq \frac{|V(G)|}{\chi_c(G)}, \quad \text{or equivalently} \quad \frac{\alpha_c(G)}{|V(G)|} \geq \frac{1}{\chi_c(G)}. \quad (1)$$

In this paper, we focus on the quantity $\alpha_c(G)/|V(G)|$, i.e., the proportion of vertices of G that we can put into a c -clustered set, and seek to find (for graphs of a particular class) universal lower bounds that significantly improve on the $1/\chi_c(G)$ in Equation (1). We shall focus on graphs of treewidth k , as introduced by Robertson and Seymour [14], while we also briefly discuss other graph classes at the very end.

Our Results. We are interested in the largest c -clustered number guaranteed in each n -vertex graph G with $\text{tw}(G) = k$, i.e., graph of treewidth k . To this end, let us define

$$x_{k,c} = \liminf\left\{\frac{\alpha_c(G)}{|V(G)|} : \text{tw}(G) = k\right\}. \quad (2)$$

In fact, for lower bounds on $x_{k,c}$ we will show the slightly stronger statement that every graph G of treewidth k satisfies $\alpha_c(G) \geq x_{k,c} \cdot |V(G)|$. Similarly, for our upper bounds on $x_{k,c}$ we shall construct an infinite set of graphs G of treewidth k with $\alpha_c(G) \leq \lceil x_{k,c} \cdot |V(G)| \rceil$ for each such G . Our results on $x_{k,c}$ are summarized in the following theorem and illustrated in Figure 2.

► **Theorem 1.** *Each of the following holds.*

1. $\frac{c}{k+c+1} \leq x_{k,c} \leq \frac{c}{k+c}$ for every $c, k \geq 1$.
2. $x_{1,c} = \frac{c}{1+c}$ for every $c \geq 1$.
3. $x_{k,1} = \frac{1}{k+1}$ and $x_{k,2} = \frac{2}{k+2}$ for every $k \geq 1$.
4. $x_{2,3} = \frac{5}{9}$.

That is, we show a general upper bound of $x_{k,c} \leq \frac{c}{k+c}$ and a general lower bound of $x_{k,c} \geq \frac{c}{k+c+1}$ that is just an additive 1 in the denominator away, cf. Item 1. We show our upper bound to be tight if $k = 1$ or $c \leq 2$, cf. Items 2–3. But somewhat surprisingly, in the smallest case $k = 2$ and $c = 3$ not covered by this, we show that $x_{2,3} = \frac{5}{9}$, cf. Item 4, which matches neither the general upper nor the general lower bound in Item 1. This leaves us with no obvious good candidate for the true value of $x_{k,c}$ in general. We wonder if there are further infinite families of parameters for which simple formulas for $x_{k,c}$ exist.

Organisation of the paper. After discussing some related work and previously known bounds on $x_{k,c}$, we start in Section 2 with a short introduction of the model for treewidth- k graphs that we primarily use in our proofs. In Section 2 we also explain that Equation (1) does not yield interesting lower bounds on $x_{k,c}$ if $c \neq 1$.

We then prove Item 1 of Theorem 1 in Section 3, Item 2 in Section 4, Item 3 in Section 5, and Item 4 in Section 6. Finally, we give a brief discussion of c -clustered independence in other classes of graphs in Section 7.

Related Work. While the c -clustered independence number $\alpha_c(G)$ has (to the best of our knowledge) not been explicitly considered before, there is a number of equivalent or closely related concepts in the literature. Most relevant to us are the following results of Wood [15], and Chappell and Pelsmajer [5].

► **Theorem 2** (Wood [15, Theorem 22]).

Let $G = (V, E)$ be a graph on n vertices and treewidth at most k . If $n \leq \lfloor \frac{p}{k+1} \rfloor (c+1) + k + c - 1$ and $k + 1 \leq p$, then there is a set $S \subseteq V$ of size p , such that all connected components of $G \setminus S$ have order at most c .

Rearranging terms, Theorem 2 proves that

$$\frac{c-k}{c+1} \leq \inf \left\{ \frac{\alpha_c(G)}{|V(G)|} : \text{tw}(G) = k \right\},$$

i.e., gives the lower bound $x_{k,c} \geq \frac{c-k}{c+1}$. As $\frac{c-k}{c+1} < \frac{c}{k+c+1}$ for all $k, c \geq 1$, the lower bound $x_{k,c} \geq \frac{c}{k+c+1}$ in Item 1 of Theorem 1 supersedes Theorem 2.

Chappell and Pelsmajer [5] investigated for $d \geq 0$ and $k \geq 1$ the largest set S of vertices in any n -vertex graph G of treewidth k , such that the induced subgraph $G[S]$ is a forest of maximum degree at most d . Equivalently, for $d = 0$, S is an independent set, and for $d = 1$, S is a 2-clustered set. (For $d \geq 2$ there is no equivalent correspondence in c -clustered sets.)

► **Theorem 3** (Chappell and Pelsmajer [5]).

Let $G = (V, E)$ be a graph on n vertices and treewidth at most k . Then there is a subset $S \subseteq V$ such that $G[S]$ has maximum degree at most 1 and

$$|S| \geq \frac{2n+2}{2k+3} \text{ if } k \geq 4 \quad \text{respectively} \quad |S| \geq \frac{2}{k+2}n \text{ if } k \leq 3.$$

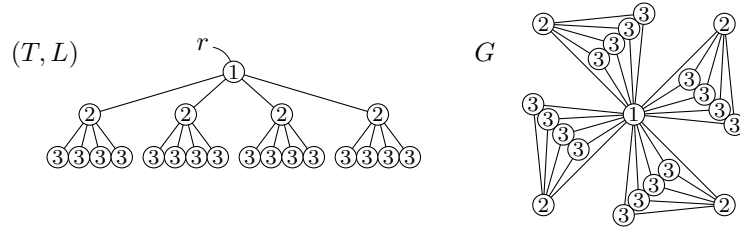
They also conjecture that their (better) bound for $k \leq 3$ should hold for all k .

► **Conjecture 4** (Chappell and Pelsmajer [5, Conjecture 13]).

For $k \geq 0$, if G is a graph of order n and treewidth at most k , then G admits an induced subgraph $G[S]$ of maximum degree at most 1 and $|S| \geq \lceil \frac{2n}{k+2} \rceil$.

We confirm Conjecture 4 in Proposition 10 below. In particular, Item 3 in Theorem 1 indeed states that $x_{k,2} \geq \frac{2}{k+2}$.

Let us also briefly mention some further notions that are related to the c -clustered sets of a graph $G = (V, E)$. Clearly, $S \subseteq V$ is 1-clustered (i.e., an independent set) if and only if its complement $V - S$ is a vertex cover. Along these lines, complements of c -clustered sets are also known as c -vertex separators [11], or c -component order connected sets [10], and for the special case of $c = 2$ as 3-path vertex covers [4]. Meanwhile, 2-clustered sets appeared under the name of dissociation sets [16].



■ **Figure 3** A graph G (right) with a k -tree model (T, L) (left) with $\chi_c(G) = k + 1$ for $c = 4$, $k = 2$.

2 Graphs of treewidth k and a first observation

All graphs considered here are finite, simple, and undirected. For a graph G and a vertex $v \in V(G)$, we denote the neighborhood of v in G by $N_G(v) = \{u \in V(G) : uv \in E(G)\}$.

For our arguments it will be convenient to rely on the definition of the treewidth of a graph in terms of k -tree models below. In a rooted tree T with root r , a vertex u is an *ancestor* of vertex v (and v is a *descendant* of u) if u lies on the unique path in T from v to r . We denote the distance between two vertices u and v by $\text{dist}(u, v)$ and call vertices in T *lower* if they have a larger distance to the root. The *height* of T is the largest distance of any vertex in T to the root plus 1.

► **Definition 5.** A k -tree model of a graph G is a rooted tree T with vertex set $V(T) = V(G)$, together with a labeling $L: V(T) \rightarrow [k + 1]$ such that for every edge $uv \in E(G)$ we have

- $L(u) \neq L(v)$ and
- u is the lowest ancestor of v with label $L(u)$, or vice versa.

The treewidth of G , denoted by $\text{tw}(G)$, is the smallest $k \in \mathbb{N}$ for which there exists a k -tree model (T, L) of G .

See Figures 3 and 4 for examples of graphs G with $\text{tw}(G) = k$ and some corresponding k -tree models (T, L) . Establishing some notation, for a fixed k -tree model (T, L) of G and a vertex v of G , the *parents* of v are those neighbors $u \in N_G(v)$ of v in G that are ancestors of v in T . Similarly, whenever u is a parent of v , then v is a *child* of u . Note that in any k -tree model (T, L) , the parents of v have pairwise distinct labels and distinct from $L(v)$. Thus, v has at most k parents, while v may have arbitrarily many children.

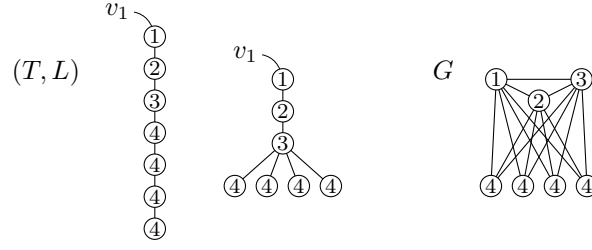
If (T, L) is a k -tree model of G , then in particular L is a proper vertex coloring of G with $k + 1$ colors. Hence, $\chi_1(G) = \chi(G) \leq \text{tw}(G) + 1$ for every graph G , which implies with Equation (1) that

$$\frac{\alpha_1(G)}{|V(G)|} \geq \frac{1}{k+1} \text{ if } \text{tw}(G) = k \quad \text{and thus} \quad x_{k,1} \geq \frac{1}{k+1}.$$

It is easy to see that in fact $x_{k,1} = \frac{1}{k+1}$, cf. Theorem 1 Item 3. However, Equation (1) does not give anything better for $c > 1$, due to the following.

► **Observation 6.** For any k, c , let T be the full c -ary tree with root r and height $k + 1$, and $L: V(T) \rightarrow [k + 1]$ the labeling given by $L(v) = \text{dist}(v, r) + 1$. See Figure 3 for an example. Then the edge-maximal graph G with k -tree model (T, L) satisfies $\chi_c(G) = k + 1$.

In fact, if ϕ is any c -clustered coloring of G and the root r receives color i , then at least one of the c subtrees below r contains no vertex of color i , and it follows by induction on k that there are at least $k + 1$ distinct colors.



■ **Figure 4** A graph G (left) with two different k -tree models (T, L) (left) with $\alpha_c(G) = c$ and $|V(G)| = k + c$, i.e., $\alpha_c(G) = \frac{c}{k+c}|V(G)|$, for $k = 3$, $c = 4$.

Observation 6 shows that for $c \neq 1$ we do not get anything better than the obvious lower bound $x_{k,c} \geq x_{k,1} \geq \frac{1}{k+1}$ from considering c -clustered chromatic numbers and the simple averaging argument in Equation (1).

3 General bounds for all k and c

Here we consider the case of any integers $k, c \geq 1$, i.e., we prove Theorem 1 Item 1, starting with the lower bound.

► **Proposition 7.** *For every $k, c \geq 1$ and every graph G of treewidth k we have $\alpha_c(G) \geq \frac{c}{k+c+1}|V(G)|$, i.e., $x_{k,c} \geq \frac{c}{k+c+1}$.*

Proof. Fix $G = (V, E)$ to be any graph of treewidth k . We proceed by induction on $n = |V|$ and find a c -clustered set S in G of size $|S| \geq \frac{c}{k+c+1}n$. For the induction base, the case $n \leq c$, it is enough to take $S = V$. So assume that $n > c$. Let (T, L) be a k -tree model of G . Let v be a lowest vertex in T that has at least c descendants. Let A be the set of descendants of v and $B = N_G(v) - A$. Then $|A| \geq c$, A is a c -clustered set in G (by the minimality in the choice of v), $|B| \leq k$, and no vertex in A is adjacent to any vertex in $G' = G - (A \cup B \cup \{v\})$.

By induction on G' , there is a c -clustered set S' of at least $\frac{c}{k+c+1}(n - |A| - |B| - 1)$ vertices in G' . Then $S = S' \cup A$ is a c -clustered set of size at least

$$\begin{aligned} & \frac{c}{k+c+1}(n - |A| - |B| - 1) + |A| \\ &= \frac{c}{k+c+1}n + \frac{k+1}{k+c+1}|A| - \frac{c}{k+c+1}(|B| - 1) \\ & \geq \frac{c}{k+c+1}n + \frac{(k+1)c}{k+c+1} - \frac{c(k+1)}{k+c+1} = \frac{c}{k+c+1}n. \quad \blacktriangleleft \end{aligned}$$

The upper bound on $x_{k,c}$ is a simple construction.

► **Observation 8.** *For any k, c , let $T = [v_1, \dots, v_{k+c}]$ be a path on $k+c$ vertices rooted at v_1 , and $L: V(T) \rightarrow [k+1]$ the labeling given by $L(v_i) = i$ for $i = 1, \dots, k$ and $L(v_i) = k+1$ for $i = k+1, \dots, k+c$. See Figure 4 for an example. Then the edge-maximal graph G with k -tree model (T, L) satisfies $\alpha_c(G) = c$ and $|V(G)| = k+c$.*

In fact, v_1, \dots, v_k are universal vertices in G and hence any set of $c+1$ vertices in G induces a connected subgraph of size $c+1$, i.e., is not c -clustered.

Taking arbitrary vertex-disjoint unions of the graph G in Observation 8, it follows that $x_{k,c} \leq \frac{c}{k+c}$. So Proposition 7 and Observation 8 together prove Theorem 1 Item 1.

4 The case of graphs of treewidth 1

We shall prove Theorem 1 Item 2. For this we shall argue that, for the case of treewidth $k = 1$, we can improve the lower bound in Proposition 7 by just slightly changing its proof. To this end, we remark that any graph G with at least one edge admits a k -tree model (T, L) with $k = \text{tw}(G)$ in which the two endpoints of any edge in T have distinct labels in L . In fact, if v is the immediate ancestor of u in T and $L(u) = L(v)$, we can change the tree (keeping all labels) by hanging the subtree T_u rooted at u under the lowest ancestor w of u with $L(w) \neq L(u)$. If there is no such ancestor, then the vertices in T_u are not connected to the remaining graph, and we can permute the labeling in T_u to give u a label distinct from $L(v)$. In either case, the result is still a k -tree model of G with fewer problematic edges.

► **Proposition 9.** *For every $c \geq 1$ and every graph G of treewidth 1 we have $\alpha_c(G) \geq \frac{c}{1+c}|V(G)|$, i.e., $x_{1,c} \geq \frac{c}{1+c}$.*

Proof. We proceed by induction on $n = |V|$ and find a c -clustered set S in G of size $|S| \geq \frac{c}{1+c}n$. For the induction base, the case $n \leq c$, it is enough to take $S = V$. So assume that $n > c$. Let (T, L) be a 1-tree model of G with the property that any edge of T connects two vertices of distinct label in L . As in the proof of Proposition 7, let v be a lowest vertex in T with a set A of at least c descendants. Then A is a c -clustered set of size $|A| \geq c$, and no vertex in A is adjacent to any vertex in $G' = G - (A \cup \{v\})$. In fact take any $w \in A$ and assume by symmetry that $L(v) = 1$. If $L(w) = 2$, then v is the only ancestor of w in $N_G(w)$. And if $L(w) = 1$, the ancestor of w in $N_G(w)$ has label 2 and is the immediate ancestor of w in T by our additional assumption on the 1-tree model.

Now by induction on G' , there is a c -clustered set S' of at least $\frac{c}{1+c}(n - |A| - 1)$ vertices in G' . Then $S = S' \cup A$ is a c -clustered set of size at least

$$\begin{aligned} \frac{c}{1+c}(n - |A| - 1) + |A| &= \frac{c}{1+c}n + \frac{1}{1+c}|A| - \frac{c}{1+c} \\ &\geq \frac{c}{1+c}n + \frac{c}{1+c} - \frac{c}{1+c} = \frac{c}{1+c}n. \quad \blacktriangleleft \end{aligned}$$

5 The case of 1-clustered and 2-clustered sets

We shall prove Theorem 1 Item 3. In fact, we already have the upper bound $x_{k,c} \leq \frac{c}{k+c}$ and need to prove a matching lower bound when $c \leq 2$. For $c = 1$, this is already given by Equation (1) and it remains to consider the case $c = 2$ here.

► **Proposition 10.** *For every $k \geq 1$ and every graph G of treewidth k we have $\alpha_2(G) \geq \frac{2}{k+2}|V(G)|$, i.e., $x_{k,2} \geq \frac{2}{k+2}$.*

Proof. Let $G = (V, E)$ be any graph of treewidth k . We proceed by induction on $n = |V(G)|$ and find a 2-clustered set S in G of size $|S| \geq \frac{2}{k+2}n$. For the induction base, the case $n \leq k + 2$, it is enough to let S be any pair of vertices. So assume that $n \geq k + 3$ and let (T, L) be a k -tree model of G . Without loss of generality assume that G is edge-maximal with model (T, L) . In particular, the parents of each vertex form a clique.

We describe a procedure that gradually determines which vertices of G to *take*, i.e., include it in the desired set S , and which to *discard*, i.e., include it in another set D . All such decisions will be irrevocable, and eventually S and D will partition V . During the course of the procedure, vertices in $V - (S \cup D)$ are called *undecided*. In order to ensure that S is a 2-clustered set we maintain the following invariant for every vertex v .

- (11) If $v \in S$, then v has no undecided children and at most one child in S . If v has a child in S , then all parents of v are in D .

Note that this indeed ensures S to be a 2-clustered set. In order to bound the size $|S|$ of S in terms of n the number of vertices in G , we use *tokens* placed on vertices. Initially, there are no tokens. Taking an undecided vertex v grants k tokens, which we can distribute on the remaining undecided vertices $V - (S \cup D \cup \{v\})$. Discarding an undecided vertex v costs 2 tokens, which we can remove from v or other undecided vertices. Thus, as soon as there are no more undecided vertices, i.e., $V = S \cup D$, we can conclude that

$$k|S| \geq \# \text{tokens granted by taking vertices} \geq \# \text{tokens spend by discarding vertices} \geq 2|D|$$

and thus

$$\frac{k}{2}|S| \geq |D| = n - |S| \quad \Rightarrow \quad \frac{k+2}{k}|S| \geq n \quad \Rightarrow \quad |S| \geq \frac{2}{k+2}n,$$

as desired.

At intermediate states we allow a negative token count at undecided vertices. But still, in order to discard a vertex v , we first must redistribute tokens so that the token count at v is at least 2, and in order to take vertex v the token count at v must be at least 0.

Initially $S = D = \emptyset$, i.e., all vertices of G are undecided. Throughout we maintain a k -tree model (T, L) for $G' = G - D$, i.e., the induced subgraph of G on all taken and undecided vertices. By discarding a vertex v , we remove v from the current k -tree model of G' by contracting v into its immediate ancestor in T , keeping the labels at all vertices (except the removed v). Note that this indeed results in a k -tree model of $G' - v$ with the set of parents of each vertex forming a clique. For convenience we shall denote the new k -tree model again by (T, L) . Recall that a parent of v is a vertex $u \in N_G(v)$ that is an ancestor of v in T . Each vertex has at most k parents but by discarding vertices, we may reduce the number of parents of other undecided (or taken) vertices.

For any undecided vertex v , let t_v denote the number of tokens at v , p_v the number of parents of v , and s_v the number of children of v that are in S . We maintain the following invariants for every undecided vertex v :

- (12) If v has undecided children or $s_v \geq 2$, then $t_v \geq s_v$.
(13) If v has no undecided children, then $t_v \geq s_v + p_v - k$.

Note that these invariants hold initially when $S = D = \emptyset$.

Let v be a lowest undecided vertex in T . I.e., all children of v (if any) are in S .

Case 1 No children of v are in S .

We have $s_v = 0$ and by (13) there are $t_v \geq s_v + p_v - k = p_v - k$ tokens at v . We take v , i.e., add v to the set S , which grants k tokens, pay $k - p_v$ of these tokens to have the token count at v at 0, and spend the remaining p_v tokens by putting 1 token on each of the p_v parents of v . This maintains the invariants.

Case 2 At least two children of v are in S .

We have $s_v \geq 2$ and by (12) there are $t_v \geq s_v \geq 2$ tokens at v . We spend 2 tokens from v to discard v , i.e., add v to the set D . The invariants are again maintained.

For the remainder we may assume that each undecided vertex either has an undecided child or exactly one child in S . Let v be again a lowest undecided vertex in T , i.e., we have $s_v = 1$, and let w denote the lowest parent of v in T .

Case 3 w has $t_w \geq 1$ tokens.

We take one token from v and one token from w and use these 2 tokens to discard w . This maintains (I3) as v loses one token but also one parent.

Case 4 w has another undecided child u different from v .

We have that u is a lowest undecided vertex in T , i.e., u has no undecided children. By (I2) w has $t_w \geq s_w \geq 0$ tokens. We take one token from u and one from v and use these 2 tokens to discard w . This maintains (I3) as u and v each lose one token but also one parent.

For the remainder we may assume that v is the only undecided child of w and that w has $t_w \leq 0$ tokens. By (I2) we have $t_w \geq s_w \geq 0$, i.e., $t_w = s_w = 0$ and w has no children in S . Thus we are left with the following case.

Case 5 w has only v as undecided child and no children in S .

In this case we rely on induction. We perform a local modification on the k -tree model (T, L) , replacing v and w by a single new vertex u . To this end, let P denote the set of all parents of v . Contract v and w into the immediate ancestor z of w in T . Add a new vertex u as a leaf to z , make $P - \{w\}$ the parents of u by giving u the label of v , put u into S and put 1 additional token on each vertex in $P - \{w\}$. This modification costs us $|P| - 1 = p_v - 1$ tokens and provides us with $t_v + t_w$ tokens from v and w , causing the total cost

$$t_v + t_w - (p_v - 1) \stackrel{(I3)}{\geq} s_v + p_v - k + 0 - p_v + 1 = 2 - k,$$

which we will balance out by taking one out of v, w and discarding the other. Our choice will be determined by induction. For now, observe that the new situation satisfies our invariants and has one vertex less. By induction we get the partition (S', D') of the set $V' = V - (S \cup D \cup \{v, w\})$ of all remaining undecided vertices.

If $S' \cap P = \emptyset$, then we discard w . Now all parents of v are in $D \cup D'$. Thus we can take v which has only $s_v = 1$ child in S . Taking v grants us k tokens and discarding w costs us 2 tokens, balancing the $2 - k$ deficit from the modification.

If $S' \cap P \neq \emptyset$, then let a be a vertex in $S' \cap P$. We want to discard v and take w . To see that this is possible, let A denote the set of all parents of w . Then $P - \{w\} \subseteq A$. Recall that $P - \{w\}$ is the set of parents of the artificial vertex u . As $S' \cup S$ is 2-clustered, $u, a \in S \cup S'$, and A forms a clique in G , it follows that $G[S' \cup S - \{u\}]$ has a component of size 1 only consisting of vertex a . As no child of w is in $S \cup S'$, we can indeed take w and discard v . Again, this grants us k tokens and costs us 2 tokens, balancing the $2 - k$ deficit from the modification.

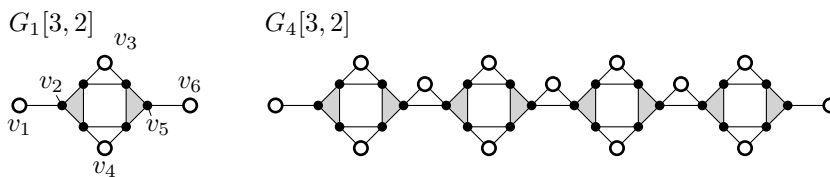
Observe that by our invariants, this complete case distinction concludes the proof. ◀

6 The case of 3-clustered sets in graphs of treewidth 2

We shall show in this section that for $k = 2$ and $c = 3$, the smallest c -clustered number of n -vertex graphs of treewidth k is $\lceil \frac{5}{9}n \rceil$, i.e., $x_{2,3} = \frac{5}{9}$. Note that for $k = 2$ and $c = 3$ we have

$$\frac{c}{k+c+1} = \frac{1}{2} < \frac{5}{9} < \frac{3}{5} = \frac{c}{k+c},$$

i.e., this value lies strictly between the general lower and upper bound in Item 1 of Theorem 1.



■ **Figure 5** Illustration of the graph G_i , $i \geq 1$, with $9i + 1$ vertices and no 3-clustered set of size more than $5i + 2$.

We start with an explicit construction for the upper bound. Let G_1 be the 10-vertex graph shown in the left of Figure 5. For an integer $i \geq 2$ let G_i be the graph obtained from i copies of G_1 by identifying vertex v_6 of each copy (except the last) with the vertex v_1 of the previous copy, and adding an edge between vertex v_5 of each copy (except the last) with vertex v_2 of the previous copy. See the right of Figure 5 for an illustration. Note that G_i has $9i + 1$ vertices and treewidth 2. In fact, each G_i is outerplanar as shown in Figure 5.

► **Proposition 11.** *For each $i \geq 1$ we have $\alpha_3(G_i) \leq 5i + 1 = \lceil \frac{5}{9}|V(G_i)| \rceil$.*

Proof. Let $S \subseteq V$ be a maximum 3-clustered set in G_i . Let A be the set of all vertices v_1, v_3, v_4, v_6 from all copies of G_1 . This is, A is the set of $3i + 1$ vertices shown in white in Figure 5. First, we claim that without loss of generality we may assume that $A \subseteq S$. So assume that $v \in A$ with $v \notin S$. By maximality of S , there is a neighbor $u \in N_G(v)$ with $u \in S$. Note that $u \notin A$, as A is an independent set in G_i . The vertices in A are the simplicial vertices of G_i , giving that $N_G(v) - u \subseteq N_G(u) - v$. Hence $S' = S - u \cup \{v\}$ is also a 3-clustered set of the same size with $|A - S'| < |A - S|$.

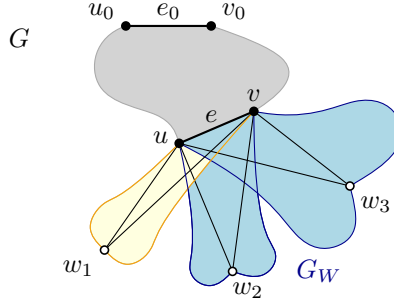
Second, the vertices in $V - A$ are partitioned into $2i$ vertex-disjoint triangles, highlighted in gray in Figure 5. Given that $A \subseteq S$ and S is 3-clustered, observe that from each such triangle there is at most one vertex in S . Thus $|S| \leq |A| + 2i = 5i + 1$, as desired. ◀

By Proposition 11 we have $x_{2,3} \leq \frac{5}{9}$. For the proof of the lower bound $x_{2,3} \geq \frac{5}{9}$ we shall show that every graph G of treewidth 2 admits a 3-clustered set of size at least $\frac{5}{9}|V(G)|$. We present this proof without using k -tree models. Instead, it will be more convenient to work with a 2-tree G rooted at some edge e_0 , i.e., a graph that can be constructed starting with e_0 by iteratively adding a new vertex to the endpoints of an already constructed edge. We consider *cut pairs* in G , i.e., edges $e = uv$ such that $G - u - v$ is disconnected. There is a connected component of $G - u - v$ for each $w \in N(u) \cap N(v)$ where those in a different component than u_0, v_0 are called the children of u and v . In terms of a 2-tree model (T, L) of G rooted at u_0 , the children of $e = uv$, say with v below u in T , are the highest vertices w in the subtree below v with the label $L(w) \notin \{L(u), L(v)\}$.

► **Proposition 12.** *For every graph $G = (V, E)$ of treewidth at most 2, we have $\alpha_3(G) \geq \frac{5}{9}|V|$.*

Proof. Since every graph of treewidth 2 is subgraph of a 2-tree, we can assume without loss of generality that G is a 2-tree. We proceed by induction on $n = |V|$. If $n = 3$, then clearly $\alpha_3(G) = 3 \geq \frac{5}{9} \cdot 3$. So assume for the remainder that $n \geq 4$.

We root G at an arbitrary edge $e_0 = u_0v_0$, and for any edge $e = uv$ in G call the common neighbors of u and v that are not in the component of $G - u - v$ that contains u_0 or v_0 the *children* of e . Every vertex $w \neq u_0, v_0$ is the child of exactly one edge $e = uv$ and we call u and v the *parents* of w . Note that for every edge one of its endpoints is a parent of the other endpoint (where by convention u_0 is the parent of v_0). Throughout this proof for each edge we always list the parent first, i.e., for any edge uv vertex u is a parent of vertex v .



■ **Figure 6** A 2-tree G rooted at edge $e_0 = u_0v_0$, an edge $e = uv$ in G , its children w_1, w_2, w_3 , and the 2-tree G_W for $W = \{w_2, w_3\}$ (blue).

For each edge $e = uv$ and each subset W of children of e , let G_W denote the subgraph of G induced by $W \cup \{u, v\}$ and all vertices that have an ancestor in W . Note that G_W is a 2-tree and we consider it rooted at edge uv . See Figure 6 for a schematic illustration.

Our goal is to find an edge $e = uv$ and a subset W of children of e for which G_W admits a 3-clustered set S_W with $S_W \cap \{u, v\} = \emptyset$ and $|S_W| \geq \frac{5}{9}|V(G_W)|$. Let us call such a set W a *good set*. For simplicity, if $|W| = 1$, i.e., $W = \{w\}$, we also write S_w and G_w instead of $S_{\{w\}}$ and $G_{\{w\}}$. Once we have a good set W , the result easily follows by induction on $G' = G - V(G_W)$. In fact, let S' be a 3-clustered set in G' of size $|S'| \geq \frac{5}{9}|V(G')|$, then $S = S' \cup S_W$ is a 3-clustered set in G of size

$$|S| = |S'| + |S_W| \geq \frac{5}{9}|V(G')| + \frac{5}{9}|V(G_W)| = \frac{5}{9}|V(G)|.$$

To find a good set, we consider edges in bottom-up order, that is, descendants before ancestors, starting with the edges that have no children. For each considered edge $e = uv$ with W being a subset of all children of e , we store a 3-clustered set S_W of G_W with $S_W \cap \{u, v\} = \emptyset$. We shall ensure that $|S_W| \geq \frac{5}{9}|V(G_W - \{u, v\})| = \frac{5}{9}(|V(G_W)| - 2)$. With this in mind, we define

$$\text{sp}(W) = 9|S_W| - 5(|V(G_W)| - 2)$$

as the *surplus* of W . Thus we shall ensure that $\text{sp}(W) \geq 0$, while if $\text{sp}(W) \geq 10$, then

$$9|S_W| \geq 5(|V(G_W)| - 2) + 10 = 5|V(G_W)| \quad \text{and thus} \quad |S_W| \geq \frac{5}{9}|V(G_W)|.$$

In other words, if $\text{sp}(W) \geq 10$, then W is good.

Looking for good sets, let us assume again that we currently consider edge $e = uv$ with a subset W of children of e . Besides determining S_W and thereby $\text{sp}(W)$, we also define the *threat* at u from W , denoted by $\text{th}_W(u)$ as the total size of all components of $G[S_W]$ that contain a neighbor of u , i.e.,

$$\text{th}_W(u) = \#\{x \in S_W : x \in C, C \text{ a component of } G[S_W], N(u) \cap C \neq \emptyset\}.$$

In other words, $S_W \cup \{u\}$ is a 3-clustered set if and only if $\text{th}_W(u) \leq 2$, i.e., the threat at u from W is at most 2. The threat $\text{th}_W(v)$ at the other endpoint v of e is defined analogously. For brevity, let us combine surplus and threats and simply say that

$$\text{the type of } W \text{ is } \alpha(s)_\beta \text{ with } \alpha = \text{th}_W(u), s = \text{sp}(W), \beta = \text{th}_W(v).$$

For example, if $W = \{w\}$ and w has no children, then we set $S_W = \{w\}$ and thus $\text{sp}(W) = 4$, $\text{th}_W(u) = \text{th}_W(v) = 1$, which gives W the type $1(4)_1$. Note that $\alpha(s)_\beta \neq \beta(s)_\alpha$ for $\alpha \neq \beta$ because we assume that u is a parent of v and not vice versa.

With these definitions in place, a good set W is one whose type $\alpha(s)_\beta$ satisfies $s \geq 10$. In the entire argument below, we shall compute the types of sets in a bottom-up approach and either find a good set or encounter and store one of the following nine different types:

$${}_0(0)_0 \quad {}_1(4)_1, \quad {}_2(8)_2, \quad {}_1(7)_2, \quad {}_2(7)_1, \quad {}_1(6)_1, \quad {}_1(9)_2, \quad {}_2(9)_1, \quad {}_1(8)_1 \quad (3)$$

The first type ${}_0(0)_0$ is used only for $W = \emptyset$ with the corresponding 3-clustered set $S_W = \emptyset$ which has a surplus of 0 and a threat of 0 at each parent. To start the process, we set this type at every edge e of G that has *no* children, i.e., for the set $W = \emptyset$ of all children of e .

We proceed to consider a single vertex w with parent edge uv , and assume that we already determined the type $\alpha_1(s_1)_{\beta_1}$ of the set X of all children of uw and the type $\alpha_2(s_2)_{\beta_2}$ of the set Y of all children of vw , and that both these types are among the nine types in (3). In each of the cases below, we shall find a good set or define a 3-clustered set S_w such that the type of $W = \{w\}$ is again one of the nine types in (3). Note that the total threat at w from the types of X and Y is $\beta_1 + \beta_2$.

Case 1 $\beta_1 + \beta_2 \leq 2$.

We set $S_w = S_X \cup S_Y \cup \{w\}$. Since $\beta_1 + \beta_2 \leq 2$, the set S_w is indeed a 3-clustered set. The corresponding surplus is calculated by

$$\begin{aligned} \text{sp}(w) &= 9|S_w| - 5(|V(G_w)| - 2) = 9(|S_X| + |S_Y| + 1) - 5(|V(G_X)| - 2 + |V(G_Y)| - 2 + 1) \\ &= 9|S_X| - 5(|V(G_X)| - 2) + 9|S_Y| - 5(|V(G_Y)| - 2) + 9 - 5 = s_1 + s_2 + 4, \end{aligned}$$

i.e., the sum of the two surpluses plus 4. Observe from the list (3) of all types, that $\text{sp}(w) \geq 10$ and thus $\{w\}$ a good set, unless we are in one of the following cases.

- If $\alpha_1(s_1)_{\beta_1} = {}_0(0)_0$ and $\alpha_2(s_2)_{\beta_2} = {}_0(0)_0$, then the type of $\{w\}$ is ${}_1(4)_1$.
- If $\alpha_1(s_1)_{\beta_1} = {}_0(0)_0$ and $\alpha_2(s_2)_{\beta_2} = {}_1(4)_1$, then the type of $\{w\}$ is ${}_2(8)_2$.
- Symmetrically, if $\alpha_1(s_1)_{\beta_1} = {}_1(4)_1$ and $\alpha_2(s_2)_{\beta_2} = {}_0(0)_0$, the type of $\{w\}$ is ${}_2(8)_2$.

In each case the type of $\{w\}$ is again on the list (3).

Case 2 $\beta_1 + \beta_2 \geq 3$.

In this case we set $S_w = S_X \cup S_Y$ and calculate the surplus

$$\begin{aligned} \text{sp}(w) &= 9|S_w| - 5(|V(G_w)| - 2) = 9(|S_X| + |S_Y|) - 5(|V(G_X)| - 2 + |V(G_Y)| - 2 + 1) \\ &= 9|S_X| - 5(|V(G_X)| - 2) + 9|S_Y| - 5(|V(G_Y)| - 2) - 5 = s_1 + s_2 - 5, \end{aligned}$$

i.e., the sum of the two surpluses minus 5. For the threats at u and v , we have $\text{th}_w(u) = \alpha_1$ and $\text{th}_w(v) = \alpha_2$. Again, observe from the list (3) of all types, that $\text{sp}(w) \geq 10$ and thus $\{w\}$ is a good set, unless we are in one of the following cases.

- If $\alpha_1(s_1)_{\beta_1} = {}_1(4)_1$ and $\alpha_2(s_2)_{\beta_2} = {}_1(7)_2$, then the type of $\{w\}$ is ${}_1(6)_1$.
- If $\alpha_1(s_1)_{\beta_1} = {}_1(4)_1$ and $\alpha_2(s_2)_{\beta_2} = {}_1(9)_2$, then the type of $\{w\}$ is ${}_1(8)_1$.
- If $\alpha_1(s_1)_{\beta_1} = {}_1(4)_1$ and $\alpha_2(s_2)_{\beta_2} = {}_2(8)_2$, then the type of $\{w\}$ is ${}_1(7)_2$.
- If $\alpha_1(s_1)_{\beta_1} = {}_1(6)_1$ and $\alpha_2(s_2)_{\beta_2} = {}_1(7)_2$, then the type of $\{w\}$ is ${}_1(8)_1$.
- If $\alpha_1(s_1)_{\beta_1} = {}_1(6)_1$ and $\alpha_2(s_2)_{\beta_2} = {}_2(8)_2$, then the type of $\{w\}$ is ${}_1(9)_2$.

Here we omitted the symmetric cases, such as if $\alpha_1(s_1)_{\beta_1} = {}_2(8)_2$ and $\alpha_2(s_2)_{\beta_2} = {}_1(4)_1$, then the type of $\{w\}$ is ${}_2(7)_1$. As before, in each case the type of $\{w\}$ is again on the list (3).

Having computed the type of each one-element subset of children of uv , we proceed to combine these to obtain, again, either a good set or a type for the set W of *all* children of uv to be one of the nine in (3). To this end, assume that we already determined the type $\alpha_1(s_1)_{\beta_1}$ of a non-empty subset X of children of uv , and the type $\alpha_2(s_2)_{\beta_2}$ of another non-empty subset Y of children of uv with $X \cap Y = \emptyset$, and that both these types are among the nine types in (3). We shall consider the set $W = X \cup Y$ now.

We set $S_W = S_X \cup S_Y$ and calculate the surplus

$$\begin{aligned} \text{sp}(w) &= 9|S_w| - 5(|V(G_w)| - 2) = 9(|S_X| + |S_Y|) - 5(|V(G_X)| - 2 + |V(G_Y)| - 2) \\ &= 9|S_X| - 5(|V(G_X)| - 2) + 9|S_Y| - 5(|V(G_Y)| - 2) = s_1 + s_2, \end{aligned}$$

i.e., the sum of the two surpluses. For the threats at u and v , we have $\text{th}_W(u) = \alpha_1 + \alpha_2$ and $\text{th}_W(v) = \beta_1 + \beta_2$. Again, observe from the list (3) of all types, that $\text{sp}(W) \geq 10$ and thus W is a good set, unless both, X and Y have type ${}_1(4)_1$. But in this case W has type ${}_2(8)_2$, which is again on the list (3).

Thus by the above, we either find a good set, or determine a 3-clustered set S_W for the set W of *all* children of uv , such that the corresponding type of W is on the list (3). Finally, we should argue that we will eventually find a good set. To this end, observe that in each of the above cases, whenever we determine a type $\alpha(s)_{\beta}$ of some set W based on two already determined types $\alpha_1(s_1)_{\beta_1}$ and $\alpha_2(s_2)_{\beta_2}$, then the new type $\alpha(s)_{\beta}$ is further right in the list (3) than both $\alpha_1(s_1)_{\beta_1}$ and $\alpha_2(s_2)_{\beta_2}$. Thus, this procedure will eventually find a good set or we have determined the type of the set W_0 of all children of the base edge u_0v_0 and it is on the list (3). In this case $S = S_{W_0} \cup \{u_0\}$ is a 3-clustered set and we have

$$9|S| = 9|S_{W_0}| + 9 = \text{sp}(W_0) + 5(|V| - 2) + 9 \geq 4 + 5|V| - 10 + 9 = 5|V| + 5.$$

In particular $|S| \geq \frac{5}{9}|V|$, as desired. ◀

6.1 Extension to larger c and k

Let us remark that the proof strategy for Proposition 11 with types, surplus, and threats can be adjusted to each fixed c and k , to certify lower bounds of the form $x_{k,c} \geq \frac{p}{q}$, and possibly also find matching upper bound examples.

For $k = 2$, fixed c and test threshold p/q , we determine (as in the proof above) for each edge uv and set W of children of uv a corresponding c -clustered set S_W . This determines a type, which includes the surplus $\text{sp}(W) = q|S_W| - p(|V(G_W)| - 2)$ and in general three (not just two) threats. The threat at u is the total size of components of $G[S_W]$ that contain a neighbor of u *but no* neighbor of v , the threat at v is symmetrical, and the common threat at u, v is the total size of components of $G[S_W]$ that contain a neighbor of u *and* a neighbor of v (hence a vertex of W).

We start with the type corresponding to $W = \emptyset$, which has surplus 0 and each threat 0. Then, we exhaustively combine two known types to a single type by **(1)** knowing the types for all children of uw and all children of vw and combining these to the type for the single children $W = \{w\}$ of uv , and **(2)** knowing the types of two disjoint subsets X, Y of children of uv and combining these to the type of $X \cup Y$. If this, as in the above proof, generates only a *finite* list of types (which implies that each surplus is non-negative) without cyclic dependencies, this proves that indeed $x_{2,c} \geq \frac{p}{q}$. On the other hand, if we encounter a type with negative surplus, then tracing back the combinations, we obtain a particular 2-tree G .

Linearly arranging copies of G , this could¹ lead to a family of 2-trees certifying that $x_{2,c} < \frac{p}{q}$.

We have implemented this strategy for $k = 2$ and small c . The obtained results suggest that the true value of $x_{2,c}$ depends on the parity of c modulo 3:

c	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$x_{2,c}$	$\frac{1}{2}$	$\frac{5}{9}$	$\frac{8}{13}$	$\frac{2}{3}$	$\frac{9}{13}$	$\frac{13}{18}$	$\frac{3}{4}$	$\frac{13}{17}$	$\frac{18}{23}$	$\frac{4}{5}$	$\frac{17}{21}$	$\frac{23}{28}$	$\frac{5}{6}$	$\frac{21}{25}$

Finally, the same approach can work for larger k , but the computational effort increases. In rooted k -trees we would have parent k -cliques K , a type would store a threat for each non-empty subset of K , and to determine the type of a single children $W = \{w\}$ of K , we would combine the known types of all children of the k -subsets of $K \cup \{w\}$ containing w . As this approach determines $x_{k,c}$ only for singular values of k and c , we did not embark upon this path.

7 Other graph classes

Let us briefly discuss other classes besides the class of treewidth- k graphs. In accordance with (2), for any graph class \mathcal{G} let us define

$$x_{\mathcal{G},c} = \liminf \left\{ \frac{\alpha_c(G)}{|V(G)|} : G \in \mathcal{G} \right\}.$$

► **Lemma 13.** *If a graph class \mathcal{G} is closed under vertex-disjoint unions and $G \in \mathcal{G}$ is k -connected on $k + c$ vertices, then $x_{\mathcal{G},c} \leq \frac{c}{k+c}$.*

Proof. Take a k -connected $G \in \mathcal{G}$ on $k + c$ vertices. Whenever we remove $k - 1$ vertices, i.e., look at $\frac{c+1}{k+c}$ vertices, we get a connected subgraph on $c + 1$ vertices. Hence, $\alpha_c(G) \leq c = \frac{c}{k+c}|V(G)|$, and taking vertex-disjoint unions of G , we conclude $x_{\mathcal{G},c} \leq \frac{c}{k+c}$. ◀

In fact, Observation 8 giving $x_{k,c} \leq \frac{c}{k+c}$ is just a special case of Lemma 13 applied to the class of all graphs of treewidth k .

Looking at the class \mathcal{P} of all planar graphs, we can also apply Lemma 13. For $c \in \{2, \dots, 6\}$ we can take a c -connected planar graph on $c + c$ vertices, which gives an upper bound of $x_{\mathcal{P},c} \leq \frac{c}{c+c}$. From $c \geq 7$ on one can even choose a 5 -connected planar graph and get an upper bound of $x_{\mathcal{P},c} \leq \frac{c}{c+5}$. These bounds are not tight in general. For instance for the icosahedron graph G (shown in the middle of Figure 1) we have $\alpha_5(G) = 6$ and $\alpha_6(G) = 7$, and taking vertex-disjoint unions of it yields the better bounds $\alpha_{\mathcal{P},5} \leq \frac{5}{12}$ and $\alpha_{\mathcal{P},6} \leq \frac{1}{2}$. For $c = 2$, Lemma 13 yields $\alpha_{\mathcal{P},2} \leq \frac{1}{3}$ by taking the octahedron (shown on the left of Figure 1), which we conjecture to be best-possible.

► **Conjecture 14.** *In every planar graph there is a set S on at least a third of the vertices, such that each vertex in S is adjacent to at most one other vertex in S , i.e., $\alpha_{\mathcal{P},2}(G) = \frac{1}{3}$.*

We remark that Conjecture 14 is implied by the Albertson-Berman Conjecture that every planar graph G admits an induced forest on at least half of the vertices [1]. In fact, any such forest would contain a 2-clustered set on at least $\frac{2}{3}$ of its vertices (hence $\frac{1}{3}$ of the vertices of G) by Item 2 of Theorem 1. Along the same lines, we get the best known lower bound by the acyclic 5-coloring of Borodin [3], which implies the existence of an induced forest on at least $\frac{2}{5}$ of the vertices. Hence, $\alpha_{\mathcal{P},2}(G) \geq \frac{2}{5} \cdot \frac{2}{3} = \frac{4}{15}$.

¹ it did, in all cases we considered

Concerning $x_{\mathcal{G},c}$ asymptotically, recall that for any graph G we have $\alpha_1(G) \leq \alpha_2(G) \leq \dots$ and hence for any graph class \mathcal{G} we have $x_{\mathcal{G},1} \leq x_{\mathcal{G},2} \leq \dots \leq 1$. Edwards and McDiarmid [7] define a graph class \mathcal{G} to be *fragmentable* if for every $\varepsilon > 0$ there exist integers c, n_0 such that each graph $G \in \mathcal{G}$ with $n \geq n_0$ vertices admits a c -clustered set of size at least $(1 - \varepsilon)n$. In other words, \mathcal{G} is fragmentable if $x_{\mathcal{G},c} \rightarrow 1$ as $c \rightarrow \infty$. Edwards and McDiarmid prove that any class with *strongly sublinear separators*² is fragmentable [7]. This includes planar graphs [12], graphs of bounded orientable genus g [8], proper minor-closed graph classes [2], k -planar graphs [9], and touching graphs of d -dimensional balls [13].

► **Observation 15.** *A graph class \mathcal{G} is fragmentable if and only if $\lim_{c \rightarrow \infty} x_{\mathcal{G},c} = 1$.*

While we might be able to derive an explicit lower bound on $\alpha_c(G)$ for any c and any $G \in \mathcal{G}$ from a proof that \mathcal{G} is fragmentable, our results suggest finding large induced subgraphs of bounded treewidth in G . For example, for any proper minor-closed class \mathcal{G} there exists a constant k such that any graph $G = (V, E)$ with $G \in \mathcal{G}$ admits a 2-coloring of V for which each monochromatic induced subgraph has treewidth at most k [6]. This gives $\alpha_c(G)/|V| \geq \frac{1}{2} \cdot x_{k,c}$ for every $c \geq 0$.

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² There exists a fixed $\varepsilon < 1$ such that every n -vertex $G \in \mathcal{G}$ has a $S \subseteq V(G)$ of size $O(n^\varepsilon)$ such that each component of $G - S$ has at most $\frac{n}{2}$ vertices.

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