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On the Book Thickness of k -Trees

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Every k -tree has book thickness at most $k + 1$, and this bound is best possible for all $k \geq 3$. Vandenbussche et al. [*SIAM J. Discrete Math.*, 2009] proved that every k -tree that has a smooth degree-3 tree decomposition with width k has book thickness at most k . We prove this result is best possible for $k \geq 4$, by constructing a k -tree with book thickness $k + 1$ that has a smooth degree-4 tree decomposition with width k . This solves an open problem of Vandenbussche et al.

MSC: 05C62, 68R10

Keywords: graph, book embedding, book thickness, pagenumber, stacknumber, treewidth, tree decomposition

1 Introduction

Consider a drawing of a graph⁽ⁱ⁾ G in which the vertices are represented by distinct points on a circle in the plane, and each edge is a chord of the circle between the corresponding points. Suppose that each edge is assigned one of k colours such that crossing edges receive distinct colours. This structure is called a k -page book embedding of G : one can also think of the vertices as being ordered along the spine of a book, and the edges that receive the same colour being drawn on a single page of the book without crossings. The *book thickness* of G , denoted by $\text{bt}(G)$, is the minimum integer k for which there is a k -page book embedding of G . Book embeddings, first defined by Ollmann (1973), are ubiquitous structures with a variety of applications; see (Dujmović and Wood, 2004) for a survey with over 50 references. A book embedding is also called a *stack layout*, and book thickness is also called *stacknumber*, *pagenumber* and *fixed outerthickness*.

This paper focuses on the book thickness of k -trees. A vertex v in a graph G is k -simplicial if its neighbourhood, $N_G(v)$, is a k -clique. For $k \geq 1$, a k -tree is a graph G such that either $G \simeq K_{k+1}$, or G has a k -simplicial vertex v and $G - v$ is a k -tree. In the latter case, we say that G is obtained from $G - v$ by *adding v onto the k -clique $N_G(v)$* .

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⁽ⁱ⁾ We consider simple, finite, undirected graphs G with vertex set $V(G)$ and edge set $E(G)$. We employ standard graph-theoretic terminology; see (Diestel, 2000). For disjoint $A, B \subseteq V(G)$, let $G[A; B]$ denote the bipartite subgraph of G with vertex set $A \cup B$ and edge set $\{vw \in E(G) : v \in A, w \in B\}$.

What is the maximum book thickness of a k -tree? Observe that 1-trees are precisely the trees. Bernhart and Kainen (1979) proved that every 1-tree has a 1-page book embedding. In fact, a graph has a 1-page book embedding if and only if it is outerplanar (Bernhart and Kainen, 1979). 2-trees are the edge-maximal series-parallel graphs. Rengarajan and Veni Madhavan (1995) proved that every series parallel graph, and thus every 2-tree, has a 2-page book embedding (also see (Di Giacomo et al., 2006)). This bound is best possible, since $K_{2,3}$ is series parallel and is not outerplanar. Ganley and Heath (2001) proved that every k -tree has a $(k+1)$ -page book embedding; see (Dujmović and Wood, 2007) for an alternative proof. Ganley and Heath (2001) also conjectured that every k -tree has a k -page book embedding. This conjecture was refuted by Dujmović and Wood (2007), who constructed a k -tree with book thickness $k+1$ for all $k \geq 3$. Vandenbussche et al. (2009) independently proved the same result. Therefore the maximum book thickness of a k -tree is k for $k \leq 2$ and is $k+1$ for $k \geq 3$.

Which families of k -trees have k -page book embeddings? Togasaki and Yamazaki (2002) proved that every graph with pathwidth k has a k -page book embedding (and there are graphs with pathwidth k and book thickness k). This result is equivalent to saying that every k -tree that has a smooth degree-2 tree decomposition⁽ⁱⁱ⁾ of width k has a k -page book embedding. Vandenbussche et al. (2009) extended this result by showing that every k -tree that has a smooth degree-3 tree decomposition of width k has a k -page book embedding. Vandenbussche et al. (2009) then introduced the following natural definition. Let $m(k)$ be the maximum integer d such that every k -tree that has a smooth degree- d tree decomposition of width k has a k -page book embedding. Vandenbussche et al. (2009) proved that $3 \leq m(k) \leq k+1$, and state that determining $m(k)$ is an open problem. However, it is easily seen that the k -tree with book thickness $k+1$ constructed in (Dujmović and Wood, 2007) has a smooth degree-5 tree decomposition with width k . Thus $m(k) \leq 4$ for all $k \geq 3$. The main result of this note is to refine the construction in (Dujmović and Wood, 2007) to give a k -tree with book thickness $k+1$ that has a smooth degree-4 tree decomposition with width k for all $k \geq 4$. This proves that $m(k) = 3$ for all $k \geq 4$. It is open whether $m(3) = 3$ or 4. We conjecture that $m(3) = 3$.

2 Construction

Theorem 1 *For all $k \geq 4$ and $n \geq 11(2k^2+1)+k$, there is an n -vertex k -tree Q , such that $\text{bt}(Q) = k+1$ and Q has a smooth degree-4 tree decomposition of width k .*

Proof: Start with the complete split graph $K_{k,2k^2+1}^*$. That is, $K_{k,2k^2+1}^*$ is the k -tree obtained by adding a set S of $2k^2+1$ vertices onto a k -clique $K = \{u_1, u_2, \dots, u_k\}$, as illustrated in Figure 1. For each vertex $v \in S$ add a vertex onto the k -clique $(K \cup \{v\}) \setminus \{u_1\}$. Let T be the set of vertices added in this step. For each $w \in T$, if v is the neighbour of w in S , then add a set $T_2(w)$ of three simplicial vertices onto the k -clique $(K \cup \{v, w\}) \setminus \{u_1, u_2\}$, add a set $T_3(w)$ of three simplicial vertices onto the k -clique $(K \cup \{v, w\}) \setminus \{u_1, u_3\}$, and add a set $T_4(w)$ of three simplicial vertices onto the k -clique $(K \cup \{v, w\}) \setminus \{u_1, u_4\}$. This step is well defined since $k \geq 4$. For each $w \in T$, let $T(w) := T_2(w) \cup T_3(w) \cup T_4(w)$. By construction, Q is a k -tree, and as illustrated in Figure 2, Q has a smooth degree-4 tree decomposition of width k .

⁽ⁱⁱ⁾ See (Diestel, 2000) for the definition of tree decomposition and treewidth. Note that k -trees are the edge maximal graphs with treewidth k . A tree decomposition of width k is *smooth* if every bag has size exactly $k+1$ and any two adjacent bags have exactly k vertices in common. Any tree decomposition of a graph G can be converted into a smooth tree decomposition of G with the same width. A tree decomposition is *degree- d* if the host tree has maximum degree at most d .

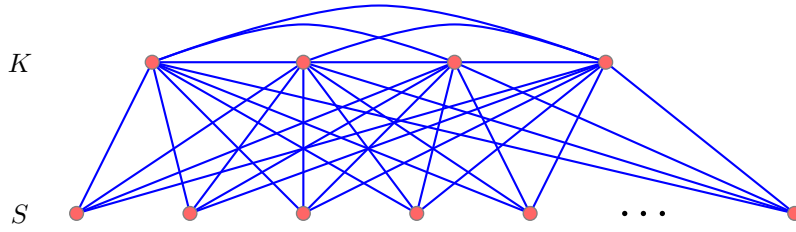


Fig. 1: The complete split graph $K_{4,|S|}^*$.

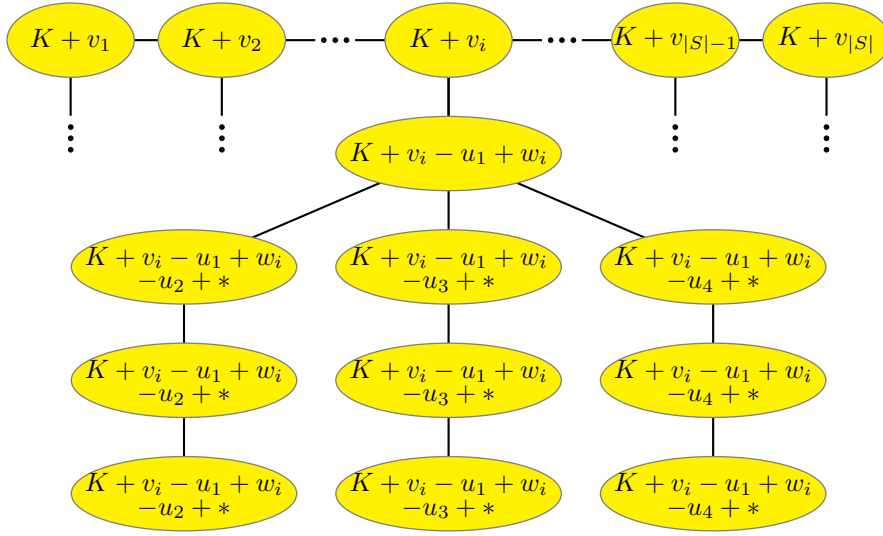


Fig. 2: A smooth degree-4 tree decomposition of Q .

It remains to prove that $\text{bt}(Q) \geq k + 1$. Suppose, for the sake of contradiction, that Q has a k -page book embedding. Say the edge colours are $1, 2, \dots, k$. For each ordered pair of vertices $v, w \in V(Q)$, let \widehat{vw} be the list of vertices in clockwise order from v to w (not including v and w).

Say $K = (u_1, u_2, \dots, u_k)$ in anticlockwise order. Since there are $2k^2 + 1$ vertices in S , by the pigeonhole principle, without loss of generality, there are at least $2k + 1$ vertices in $S \cap \widehat{u_1 u_k}$. Let $(v_1, v_2, \dots, v_{2k+1})$ be $2k + 1$ vertices in $S \cap \widehat{u_1 u_k}$ in clockwise order.

Observe that the k edges $\{u_i v_{k-i+1} : 1 \leq i \leq k\}$ are pairwise crossing, and thus receive distinct colours, as illustrated in Figure 3(a). Without loss of generality, each $u_i v_{k-i+1}$ is coloured i . As illustrated in Figure 3(b), this implies that $u_1 v_{2k+1}$ is coloured 1, since $u_1 v_{2k+1}$ crosses all of $\{u_i v_{k-i+1} : 2 \leq i \leq k\}$ which are coloured $2, 3, \dots, k$. As illustrated in Figure 3(c), this in turn implies that $u_2 v_{2k}$ is coloured 2, and so on. By an easy induction, $u_i v_{2k+2-i}$ is coloured i for each $i \in \{1, 2, \dots, k\}$, as illustrated in Figure 3(d). It follows that for all $i \in \{1, 2, \dots, k\}$ and $j \in \{k - i + 1, k - i + 2, \dots, 2k + 2 - i\}$, the edge $u_i v_j$ is coloured i , as illustrated in Figure 3(e). Moreover, as illustrated in Figure 3(f):

If $qu_i \in E(Q)$ and $q \in \widehat{v_k v_{k+2}}$, then qu_i is coloured i . (★)

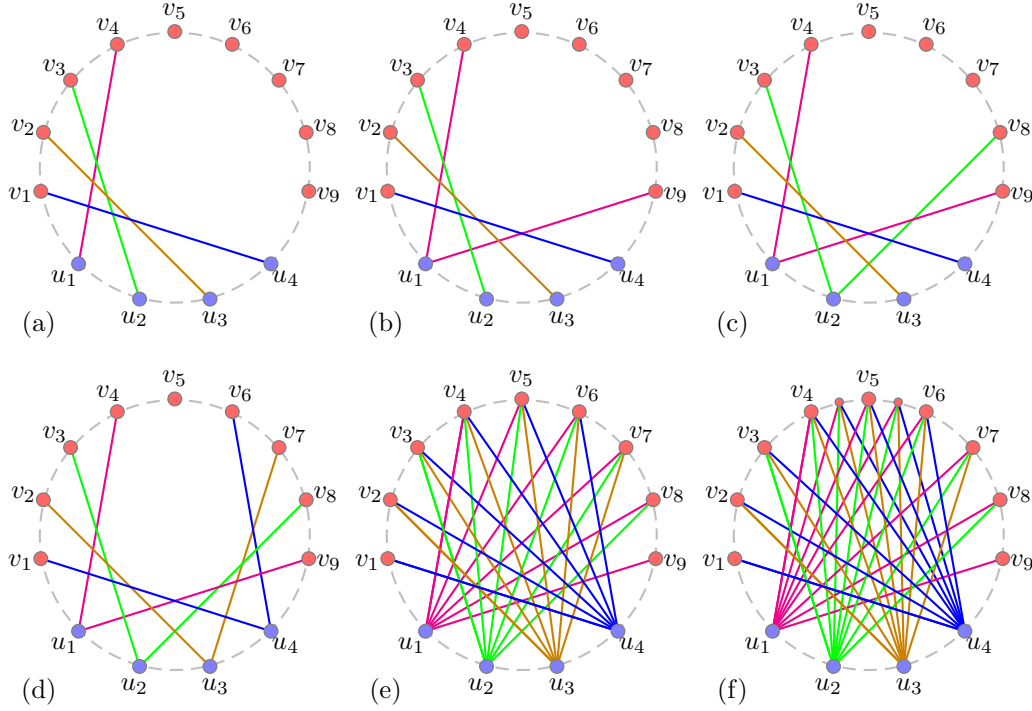


Fig. 3: Illustration of the proof of Theorem 1 with $k = 4$.

Note that the argument up to now is the same as in (Dujmović and Wood, 2007). Let w be the vertex in T adjacent to v_{k+1} . Recall that w is adjacent to each vertex in $K \setminus \{u_1\}$. Vertex w is in $\widehat{v_k v_{k+2}}$, as otherwise the edge wv_{k+1} crosses k edges of $Q[\{v_k, v_{k+2}\}; K]$ that are all coloured differently. Without loss of generality, w is in $\widehat{v_k v_{k+1}}$. Each vertex $x \in T(w)$ is in $\widehat{v_k v_{k+1}}$, as otherwise xw crosses k edges in $Q[\{v_k, v_{k+1}\}; K]$ that are all coloured differently. Therefore, all nine vertices in $T(w)$ are in $\widehat{v_k v_{k+1}}$. By the pigeonhole principle, at least one of $\widehat{v_k w}$ or $\widehat{wv_{k+1}}$ contains two vertices from $T_i(w)$ and two vertices from $T_j(w)$ for some $i, j \in \{2, 3, 4\}$ with $i \neq j$. Let x_1, x_2, x_3, x_4 be these four vertices in clockwise order in $\widehat{v_k w}$ or $\widehat{wv_{k+1}}$.

Case 1. x_1, x_2, x_3 and x_4 are in $\widehat{v_k w}$: By (★), the edges in $Q[\{w\}; K]$ are coloured $2, 3, \dots, k$. Thus x_2v_{k+1} , which crosses all the edges in $Q[\{w\}; K]$, is coloured 1. At least one of the vertices in $\{x_2, x_3, x_4\}$ is adjacent to $\{K \setminus \{u_1, u_i\}\}$ and at least one to $\{K \setminus \{u_1, u_j\}\}$. Thus, by (★), the edges in $Q[\{x_2, x_3, x_4\}; K]$ are coloured $2, 3, \dots, k$. Thus x_1w , which crosses all the edges of $Q[\{x_2, x_3, x_4\}; K]$ is coloured 1. Thus x_2v_{k+1} and x_1w cross and are both coloured 1, which is the desired contradiction.

Case 2. x_1, x_2, x_3 and x_4 are in $\widehat{wv_{k+1}}$: As in Case 1, the edges in $Q[\{x_2, x_3, x_4\}; K]$ are coloured $2, 3, \dots, k$. Thus x_1v_{k+1} , which crosses all the edges in $Q[\{x_2, x_3, x_4\}; K]$, is coloured 1. Since the edges in $Q[\{x_1, x_2, x_3\}; K]$ are coloured $2, 3, \dots, k$, the edge x_4w , which crosses all the edges of

$Q[\{x_1, x_2, x_3\}; K]$, is coloured 1. Thus x_1v_{k+1} and x_4w cross and are both coloured 1, which is the desired contradiction.

Finally, observe that $|V(Q)| = |K| + |S| + |T| + \sum_{w \in Q} |T(w)| = |K| + 11|S| = k + 11(2k^2 + 1)$. Adding more k -simplicial vertices to Q does not reduce its book thickness. Moreover, it is simple to verify that the graph obtained from Q by adding simplicial vertices onto K has a smooth degree-4 tree decomposition of width k . Thus for all $n \geq 11(2k^2 + 1) + k$, there is a k -tree G with n vertices and $\text{bt}(G) = k + 1$ that has the desired tree decomposition. \square

3 Final Thoughts

For $k \geq 3$, the minimum book thickness of a k -tree is $\lceil \frac{k+1}{2} \rceil$ (since every k -tree contains K_{k+1} , and $\text{bt}(K_{k+1}) = \lceil \frac{k+1}{2} \rceil$; see (Bernhart and Kainen, 1979)). However, we now show that the range of book thicknesses of sufficiently large k -trees is very limited.

Proposition 1 *Every k -tree G with at least $\frac{1}{2}k(k+1)$ vertices has book thickness $k-1$, k or $k+1$.*

Proof: Ganley and Heath (2001) proved that $\text{bt}(G) \leq k+1$. It remains to prove that $\text{bt}(G) \geq k-1$ assuming $|V(G)| \geq \frac{k(k+1)}{2}$. Numerous authors (Bernhart and Kainen, 1979; Cottafava and D'Antona, 1984; Keys, 1975) observed that $|E(G)| < (\text{bt}(G) + 1)|V(G)|$ for every graph G . Thus

$$(k-1)|V(G)| \leq k|V(G)| - \frac{1}{2}k(k+1) = |E(G)| < (\text{bt}(G) + 1)|V(G)| .$$

Hence $k-1 < \text{bt}(G) + 1$. Since k and $\text{bt}(G)$ are integers, $\text{bt}(G) \geq k-1$. \square

We conclude the paper by discussing some natural open problems regarding the computational complexity of calculating the book thickness for various classes of graphs.

Proposition 1 begs the question: Is there a characterisation of the k -trees with book thickness $k-1$, k or $k+1$? And somewhat more generally, is there a polynomial-time algorithm to determine the book thickness of a given k -tree? Note that the k -th power of paths are an infinite class of k -trees with book thickness $k-1$; see (Swaminathan et al., 1995).

k -trees are the edge-maximal chordal graphs with no $(k+2)$ -clique, and also are the edge-maximal graphs with treewidth k . Is there a polynomial-time algorithm to determine the book thickness of a given chordal graph? Is there a polynomial-time algorithm to determine the book thickness of a given graph with bounded treewidth?

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