A characterization of $K_{2,4}$-minor-free graphs

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Abstract

We provide a complete structural characterization of $K_{2,4}$-minor-free graphs. The 3-connected $K_{2,4}$-minor-free graphs consist of nine small graphs on at most eight vertices, together with a family of planar graphs that contains $K_4$ and, for each $n \geq 5$, $2n - 8$ nonisomorphic graphs of order $n$. To describe the 2-connected $K_{2,4}$-minor-free graphs we use $xy$-outerplanar graphs, graphs embeddable in the plane with a Hamilton $xy$-path so that all other edges lie on one side of this path. We show that, subject to an appropriate connectivity condition, $xy$-outerplanar graphs are precisely the graphs that have no rooted $K_{2,2}$-minor where $x$ and $y$ correspond to the two vertices on one side of the bipartition of $K_{2,2}$. Each 2-connected $K_{2,4}$-minor-free graph is then (i) outerplanar, (ii) the union of three $xy$-outerplanar graphs and possibly the edge $xy$, or (iii) obtained from a 3-connected $K_{2,4}$-minor-free graph by replacing each edge $x_iy_i$ in a set $\{x_1y_1, x_2y_2, \ldots, x_ky_k\}$ satisfying a certain condition by an $x_iy_i$-outerplanar graph.

1 Introduction

The Robertson-Seymour Graph Minors project has shown that minor-closed classes of graphs are the same as classes with finitely many forbidden minors. So characterizations of graphs without one or two specific minors form natural starting points for investigation. The first such result was Wagner’s demonstration $^1$

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that planar graphs are precisely the graphs that are $K_5$- and $K_{3,3}$-minor-free. From this one can show that a 3-connected graph is $K_{3,3}$-minor-free if and only if it is $K_5$ or planar. A simple well-known consequence is that a 2-connected graph is $K_{2,3}$-minor-free if and only if it is $K_4$ or outerplanar. Dirac \[7\] characterized all $K_4$-minor-free graphs. Recently there have been a number of results characterizing $H$-minor-free graphs for specific graphs $H$; one notable set of results is the systematic investigation by Ding and Liu \[5\] of all 3-connected graphs $H$ on at most eleven edges. In this paper we characterize all $K_{2,4}$-minor-free graphs.

It is also useful to investigate rooted minors, where particular vertices of $G$ must correspond to certain vertices of $H$ when we find $H$ as a minor in $G$. For example, Robertson and Seymour \[12\] characterized all 3-connected graphs that have no $K_{2,3}$ minor rooted at the three vertices on one side of the bipartition. Fabila-Monroy and Wood \[8\] characterized 3-connected graphs with no $K_4$ minor rooted at all four vertices. Demasi \[3\] characterized all 3-connected planar graphs with no $K_{2,4}$ minor rooted at the four vertices on one side of the bipartition. As part of our work in this paper we characterize all graphs with no $K_{2,2}$ minor rooted at two vertices on one side of the bipartition.

For $K_{2,4}$-minor-free graphs, or $K_{2,4}$-minor-free graphs in general, there are several known structural results. Dieng and Gavoille (see Dieng’s thesis \[4\]) showed that every 2-connected $K_{2,4}$-minor-free graph contains two vertices whose removal leaves the graph outerplanar. In 2010, Streib and Young \[14\] used Dieng results. Dieng and Gavoille (see Dieng’s thesis \[4\]) showed that every 2-connected $K_{2,4}$-minor-free graph contains two vertices whose removal leaves the graph outerplanar. In 2003 Myers \[10\] proved that a $K_{2,4}$-minor-free graph $G$ with $t \geq 10^{19}$ satisfies $|E(G)| \leq \frac{1}{2}(t + 1)(n - 1)$; more recently Chudnovsky, Reed and Seymour \[2\] showed that this is valid for all $t \geq 2$, and provided stronger bounds for 2-, 3- and 5-connected graphs. In 2006 Chen et al. \[1\] proved that 2-connected $K_{2,4}$-minor-free graphs have a cycle of length at least $n/t^{t-1}$. An unpublished paper of Ding \[6\] proposes that $K_{2,4}$-minor-free graphs can be built from slight variations of outerplanar graphs and graphs of bounded order by adding ‘strips’ and ‘fans’ using an operation that is a variant of a 2-sum (and which corresponds to the idea of replacing subdividable edges later in this paper).

We begin with some definitions and notation. All graphs $G$ are simple graphs. We use ‘$ackslash$’ to denote set difference and deletion of vertices from a graph, ‘$ackslash$’ to denote deletion of edges, ‘/’ to denote contraction of edges, and ‘+’ to denote both addition of edges and join of graphs.

A graph $H$ is a minor of a graph $G$ if $H$ is isomorphic to a graph formed from $G$ by contracting and deleting edges of $G$ and deleting isolated vertices of $G$. We delete multiple edges and loops, so all minors are simple. Another way to think of a $k$-vertex minor $H$ of $G$ is as a collection of disjoint subsets of the vertices of $G$, $(V_1, V_2, \ldots, V_k)$ where each $V_i$ corresponds to a vertex $v_i$ of $H$, where $G[V_i]$ (the subgraph of $G$ induced by the vertex set $V_i$) is connected for $1 \leq i \leq k$, and for each edge $v_i v_j \in E(H)$ there is at least one edge between $V_i$ and $V_j$ in $G$. We call this an edge-based model of $H$ in $G$. More generally, we may allow there to be a path $P_i$ rather than an edge between $V_i$ and $V_j$ in $G$ if $v_i v_j \in E(H)$. We then require that each path $P_i$ be internally disjoint from all other such paths and from $V_1, \ldots, V_k$. We call this a path-based model of $H$ in $G$. We will often identify minors in graphs by describing the sets $(V_1, V_2, \ldots, V_k)$. The set $V_i$ is known as the branch set of $v_i$, and may be thought of as the set of vertices in $G$ that contracts to $v_i$ in $H$. A minor $H$ of $G$ is rooted at a set $S \subseteq V(G)$ if each $v \in S$ belongs to the branch set of a specified vertex $f(v) \in V(H)$. A graph is $H$-minor-free if it does not contain $H$ as a minor. A $k$-separation in a graph $G$ is a pair $(H, J)$ of edge-disjoint subgraphs of $G$ with $G = H \cup J$, $|V(H) \cap V(J)| = k$, $V(H) - V(J) \neq \emptyset$, and $V(J) - V(H) \neq \emptyset$.

Suppose $K_{2,t}$ has bipartition $(\{a_1, a_2\}, \{b_1, b_2, \ldots, b_t\})$. Let $R_1$ and $R_2$ be the branch sets of $a_1$ and $a_2$ in an edge-based model of $K_{2,t}$ in a graph $G$. Suppose $B$ is the branch set of $b_i$ for some $i$. Then there is a path $v_1 v_2 \ldots v_k$, $k \geq 3$, with $v_1 \in R_1$, $v_k \in R_2$, and $v_i \in B$ for $2 \leq i \leq k - 1$. Let $B' = \{v_2\}$ and let $R_2' = R_2 \cup \{v_3, \ldots, v_{k-1}\}$. We can replace $B$ with $B'$ and $R_2$ with $R_2'$ and still have an edge-based model of $K_{2,t}$ (possibly using fewer vertices of $G$ than before). Hence without loss of generality we may assume that the branch set of each vertex $b_i$, $1 \leq i \leq t$, is a single vertex $s_i$. Let $S = \{s_1, s_2, \ldots, s_t\}$. We say $(R_1, R_2; S)$ represents a standard (edge-based) $K_{2,t}$ minor. Observe that $G$ contains a $K_{2,t}$ minor if and only
if $G$ contains a standard $K_{2,t}$ minor. Note that the standard model also applies to $K_{2,t}$ minors rooted at two vertices corresponding to $a_1$ and $a_2$.

A wheel is a graph $W_n = K_1 + C_{n-1}$ with $n \geq 4$. A vertex of degree $n-1$ in $W_n$ is a hub and its incident edges are spokes while the remaining edges form a rim. In $W_4 = K_4$ every vertex is a hub and every edge is both a spoke and a rim edge, but in $W_n$ for $n \geq 5$ there is a unique hub and the edges are partitioned into spokes and rim edges. Note that we identify wheels by their number of vertices, rather than their number of spokes.

A graph is outerplanar if it has an outerplane embedding, an embedding in the plane with every vertex on the outer face.

In the next section, we define a class of graphs and describe several small examples which together make up all 3-connected $K_{2,4}$-minor-free graphs. We begin with 3-connected graphs because all 4-connected graphs on at least six vertices have a $K_{2,4}$ minor. This is obvious for complete graphs. Otherwise, a pair of nonadjacent vertices and the four internally disjoint paths between them guaranteed by Menger’s Theorem yield a $K_{2,4}$ minor. In Section 3 we extend the characterization to 2-connected graphs. The generalization to all graphs follows because a graph that is not 2-connected is $K_{2,4}$-minor-free if and only if each of its blocks is $K_{2,4}$-minor-free.

## 2 The 3-connected case

All graphs $G$ with $|V(G)| < 6$ are trivially $K_{2,4}$-minor-free; the 3-connected ones are $K_5$, $K_5 \setminus e$, $W_5$, and $K_4 = W_4$. For $|V(G)| \geq 6$, first we define a class of graphs and identify those that are 3-connected and $K_{2,4}$-minor-free. We then look at some small graphs that do not fit into this class. Finally, we show that every 3-connected $K_{2,4}$-minor-free graph is one of these we have described.

### 2.1 A class of graphs $G^{(+)\text{r,s}}$

For $n \geq 3$ and $r, s \in \{0, 1, \ldots, n - 3\}$, let $G^{(+)\text{r,s}}$ consist of a spanning path $v_1v_2\ldots v_n$, which we call the spine, and edges $v_iv_{i-1}$ for $1 \leq i \leq r$ and $v_{n+j}v_{1+j}$ for $1 \leq j \leq s$. The graph $G^{(+)\text{r,s}}_n$ is $G^{(+)\text{r,s}} + v_1v_n$; we call $v_1v_n$ the plus edge. All graphs $G^{(+)\text{r,s}}$ are planar. Examples are shown in Figure 1. Since $G^{(+)\text{r,s}}_n \cong G^{(+)\text{s,r}}_n$ we often assume $r \leq s$.

In the following three lemmas we first determine when a graph $G^{(+)\text{r,s}}_n$ is 3-connected, and then when it is $K_{2,4}$-minor-free.

**Lemma 2.1.** For $n \geq 4$, $G = G^{(+)\text{r,s}}_n$ is 3-connected if and only if (i) $r = 1$, $s = n - 3$, and the plus edge is present (or symmetrically $s = 1$, $r = n - 3$, and the plus edge is present) or (ii) $r, s \geq 2$ and $r + s \geq n - 2$.

**Proof.** To prove the forward direction, assume $G$ is 3-connected and first suppose $r = 1$. If the plus edge is not present, then $v_1$ has degree two and $\{v_2, v_{n-1}\}$ is a 2-cut. Similarly if $s \leq n - 4$, then $v_{n-2}$ has degree two and $\{v_{n-3}, v_{n-1}\}$ is a 2-cut. Next suppose $r, s \geq 2$. If $r + s \leq n - 3$, then there is necessarily a degree two vertex $v_i$ with $4 \leq i \leq n - 3$ and hence a 2-cut in $G$. 

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Figure 1
To prove the reverse direction, assume (i) or (ii) and consider a possible 2-cut. Since \( G - \{v_1, v_2\} \) contains a spanning path, \( \{v_1, v_2\} \) is not a 2-cut. Similarly, \( \{v_{n-1}, v_n\} \) and \( \{v_1, v_n\} \) are not 2-cuts. If \( 2 < i < n \) then \( G - \{v_i, v_i\} \) contains the path \( v_{i+1}v_{i+2}\ldots v_nv_{v_3}\ldots v_{i-1} \), so \( \{v_1, v_i\} \) is not a 2-cut. Similarly, \( \{v_i, v_n\} \) is not a 2-cut for \( 1 < i < n - 1 \).

Finally consider a possible 2-cut \( \{v_i, v_j\} \), with \( 1 < i < j < n \). First assume \( j = i + 1 \). If \( n = 4 \), then \( i = 2, j = 3 \) and \( r = s = 1 \) and therefore the plus edge \( v_1v_4 \) is present; hence \( G - \{v_2, v_4\} \) is connected and \( \{v_2, v_4\} \) is not a 2-cut. Now \( n \geq 5 \) so either \( j \neq n - 1 \) or \( j \neq 2 \). Without loss of generality, say \( j \neq n - 1 \); then all vertices other than \( v_i \) or \( v_j \) lie on the paths \( v_1v_2\ldots v_{i-1} \) and \( v_{j+1}v_{j+2}\ldots v_n \), which are connected by the edge \( v_1v_{v_n-1} \). Next assume \( j \neq i + 1 \). Then there is a vertex between \( v_i \) and \( v_j \) and since \( r + s \geq n - 2 \), all vertices between \( v_i \) and \( v_j \) must be adjacent to \( v_1 \) or \( v_n \). In particular, \( v_{i+1} \neq v_j \) must be adjacent to either \( v_1 \) or \( v_n \). The two situations are similar, so without loss of generality, assume \( v_{i+1} \) is adjacent to \( v_1 \).

When \( i 
eq 2 \), the paths \( v_1v_2\ldots v_{i-1}, v_{i+1}v_{i+2}\ldots v_{j-1} \), and \( v_{j+1}v_{j+2}\ldots v_n \) are connected by \( v_1v_{i+1} \) and \( v_2v_n \).

When \( i = 2 \) they are connected by \( v_1v_{i+1} \) and either \( v_1v_n \) (if \( s = 1 \), forcing the plus edge) or \( v_{i+1}v_3v_n \) (if \( s \geq 2 \)).

\[ \square \]

**Lemma 2.2.** For \( n \geq 6 \), \( G = G_{n,r,s}^{(+)r} \) is \( K_{2,4} \)-minor-free if and only if \( r + s \leq n - 1 \).

**Proof.** To prove the forward direction, suppose \( r + s \geq n \). Then there are vertices \( v_i \) and \( v_{i+1} \) such that both \( v_1 \) and \( v_n \) are adjacent to both \( v_i \) and \( v_{i+1} \) and \( 3 \leq i \leq n - 3 \). Then there is a standard \( K_{2,4} \) minor \((R_1, R_2; S)\) in \( G \): let \( S = \{v_2, v_{i+1}, v_{n-1}\} \), \( R_1 = \{v_1\} \), and \( R_2 = \{v_n\} \).

Now suppose that \( r + s \leq n - 1 \). We claim that if \( G \) has a standard \( K_{2,4} \) minor \((R_1, R_2; S)\), then \( v_1 \in R_1 \) and \( v_n \in R_2 \) (or vice versa). The graph \( G - v_1 \) is outerplanar and thus has no \( K_{2,3} \) minor. Therefore, if \( G \) has a \( K_{2,4} \) minor, then it must include \( v_1 \). We cannot have \( v_1 \in S \) because then the outerplanar graph \( G - v_1 \) would have a \( K_{2,3} \) minor. By symmetry, \( v_n \) must also be included in the minor and \( v_i \notin S \). If \( v_1, v_n \in R_i \), then \( G - \{v_1, v_n\} \) has a \( K_{1,4} \) minor, but \( G - \{v_1, v_n\} \) is a path and there is no \( K_{1,4} \) minor in a path. The only remaining possibility is \( v_1 \in R_1 \) and \( v_n \in R_2 \) (or vice versa).

Let \( N(v) \) denote the set of neighbors of \( v \). Let \( A = N(v_1) - \{v_2\} = \{v_{n-r}, v_{n-r+1}, \ldots, v_{n-1}\} \) and \( B = N(v_n) - \{v_{n-1}\} = \{v_2, v_3, \ldots, v_{s+1}\} \), which intersect only if \( v_{n-r} = v_{s+1} \). Suppose \( G \) has a standard \( K_{2,4} \) minor \((R_1, R_2; S)\). Then by the claim proved in the previous paragraph, \( v_1 \in R_1 \) and \( v_n \in R_2 \). We consider the makeup of \( S \). Suppose \( \{s_1, s_2, s_3\} \subseteq S \cap A \), in that order along the spine. Since \( \{v_1, s_1, s_3\} \subseteq R_1 \cup \{s_1, s_3\} \) separates \( s_2 \) and \( v_n \), and \( v_n \in R_2 \), we cannot have \( R_2 \) adjacent to \( s_2 \), which is a contradiction. Thus \( |S \cap A| \leq 2 \). Symmetrically, \( |S \cap B| \leq 2 \). We must have \( s_1, s_2 \in S \cap A \) and \( s_3, s_4 \in S \cap B \) in the order \( s_3, s_4, s_2, s_1 \) along the spine. Since \( v_n \in R_2 \), there must be a \( v_n \)-2-path in \( G - \{v_1, s_1, s_3, s_4\} \), and hence \( s_3 \neq s_{n+1} \). Then \( v_{n+1} \) is a cutvertex separating \( v_n \) and \( s_2 \) in \( G - \{v_1, s_1, s_3, s_4\} \), so \( v_{n+1} \in R_2 \). Now there must also be a \( v_1 \)-2-path in \( G - \{v_n, v_{n+1}, s_4\} \) but no such path exists. Thus there is no \( K_{2,4} \) minor.

\[ \square \]

Define \( \mathcal{G} \) to be the set of (labeled) graphs of the form \( G_{n,r,s}^{(+)r} \) that are both 3-connected and \( K_{2,4} \)-minor-free. Of the four 3-connected graphs on fewer than six vertices, three are planar, and all three belong to \( \mathcal{G} \): \( K_3 \), \( \mathcal{G}^{(+)r}_{5,2,2} \), \( W_5 \cong \mathcal{G}^{(+)r}_{5,1,2} \cong \mathcal{G}^{(+)r}_{5,2,1} \), and \( K_4 = W_4 \cong \mathcal{G}^{(+)r}_{4,1,1} \). From this and Lemma 2.1 and 2.2 we get

\[ \mathcal{G} = \{G_{n,n-3,4}^{(+)r}, G_{n,n-3,1}^{(+)r} : n \geq 4\} \cup \{G_{n,r,s}^{(+)r} : n \geq 5, r, s \in \{2, 3, \ldots, n - 3\}, r + s = n - 1 \text{ or } n - 2\}. \]

Let \( \mathcal{G} \) denote the class of all graphs isomorphic to a graph in \( \mathcal{G} \).

There are some isomorphisms between graphs in \( \mathcal{G} \) and also symmetries within certain graphs of the class. Let \( \rho = \rho_n \) be the involution with \( \rho(v_i) = v_{i+1} \) for \( 1 \leq i \leq n \). Then \( \rho \) provides the isomorphism (in both directions) between \( G_{n,r,s}^{(+)r} \) and \( G_{n,s,r}^{(+)r} \) that we have already noted; if \( r = s \) it is an automorphism. The graph \( G_{n,1,n-3}^{(+)r} \) is isomorphic to \( W_n \), with \( v_n \) as a hub. It has the obvious symmetries.

Define \( \sigma = \sigma_n \) to be the involution fixing \( v_{n-1} \) and \( v_n \) and with \( \sigma(v_i) = v_{i+1} \) for \( 1 \leq i \leq n - 2 \). Then \( \sigma \) is an automorphism of \( G_{n,2,n-4} \), an isomorphism (in both directions) between \( G_{n,2,n-4}^{(+)r} \) and \( G_{n,2,n-3} \), and an
Corollary 2.5. Every minor of a graph in $\mathcal{G}$ is a subgraph of some graph in $\tilde{\mathcal{G}}$.  

Figure 2  

automorphism of $G_{n,2,n-3}^+$. The case $n=9$ is illustrated in Figure 2, where $\sigma = \sigma_9$ corresponds to reflection about a vertical axis. The graph without the dashed edges $e_1$ and $e_2$ is $G_{9,2,5}$. With the edge $e_1$, the graph is $G_{9,2,5}^+$ and with $e_2$, the graph is $G_{9,2,6}$. With both edges $e_1$ and $e_2$, the graph is $G_{9,2,6}^+$. In general $\sigma$ maps the spine $P = v_1v_2\ldots v_n$ to the path $\sigma(P) = v_{n-2}v_{n-3}\ldots v_2v_1w_{n-1}v_n$. For $G_{n,r,s}^{(e)}$ with $r=2$ we call $\sigma(P)$ the second spine. When $s=2$ we have a similar involution $\sigma'$, and the path $\sigma'(P) = v_1v_2v_nv_{n-1}\ldots v_4v_3$ can be regarded as an extra spine. When $r=s=2$, $\sigma'(P)$ is the image of $\sigma(P)$ under the automorphism $\rho$. 

Finally, besides some obvious special symmetries when $n=4$ or $5$, $G_{6,2,2}$ is vertex-transitive and is isomorphic to the triangular prism.

These symmetries and isomorphisms will be important later, particularly in Section 3 when we discuss which edges of $G \in \mathcal{G}$ can be subdivided without creating a $K_{2,4}$ minor. Up to isomorphism the class $\mathcal{G}$ contains one 4-vertex graph and $2n-8$ $n$-vertex graphs for each $n \geq 5$.

We now examine the effect of deleting or contracting a single edge of a graph in $\mathcal{G}$.

Lemma 2.3. Suppose $G = G_{n,r,s}^{(e)}$ and $e \in E(G)$. The following are equivalent.

(i) $G \backslash e \in \mathcal{G}$.

(ii) $G \backslash e$ is 3-connected.

(iii) $G$ is not a wheel and either $e$ is a plus edge, or $r+s = n-1$ and $e \in \{v_1v_{n-r},v_nv_{1+s}\}$.

Proof. Clearly (iii) $\Rightarrow$ (i) $\Rightarrow$ (ii). If (iii) does not hold then $G \backslash e$ has at least one vertex of degree two, so (ii) does not hold; thus (ii) $\Rightarrow$ (iii). \qed

Now consider contracting an edge $e$ of $G = G_{n,r,s}^{(e)}$. If $n=4$ then $G = K_4$ and $G/e \cong K_3$ for any edge $e$, so assume that $n \geq 5$. If $G$ is a wheel $W_n$ then we obtain $W_{n-1}$ if we contract a rim edge, and $K_1 + P_{n-2}$ if we contract a spoke. Therefore assume $G$ is not a wheel, so $r,s \geq 2$. The effects of contracting edges in this case are shown in Table 1. Here the superscript $(+)$ means that the plus edge is present in $G/e$ precisely if it is present in $G$. Edges not included in the table are covered by the symmetry $\rho$ that swaps $r$ and $s$, $v_i$ and $v_{n+1-i}$. We may summarize the results as follows.

Lemma 2.4. Suppose $G = G_{n,r,s}^{(e)} \in \mathcal{G}$ and $e \in E(G)$.

(i) If $n \geq 5$ then $G/e$ is isomorphic to a graph in $\mathcal{G}$ with at most one edge deleted.

(ii) If $n \geq 4$ then $G/e \in \bar{\mathcal{G}}$ if and only if $G/e$ is 3-connected.

(iii) If $G$ is a wheel with $n \geq 5$ then some $G/e$ is isomorphic to $W_{n-1}$, and every $G/e \in \bar{\mathcal{G}}$ is isomorphic to $W_{n-1}$. If $G$ is not a wheel then (from the starred entries in Table 1) some $G/e$ is isomorphic to each of $G_{n-1,r-1,min(s,n-4)}, G_{n-1,min(r,n-4),s-1}$ and, if $r+s = n-2$, also $G_{n-1,r,s}^{(+)}$ is isomorphic to a spanning subgraph of one of these.

Now we apply these results to the structure of minors of graphs in $\mathcal{G}$ or $\bar{\mathcal{G}}$.

Corollary 2.5. Every minor of a graph in $\mathcal{G}$ is a subgraph of some graph in $\bar{\mathcal{G}}$. 

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Table 1: Contracting an edge $e$ in $G = G_{n,r,s}^{(+)}$ with $r, s \geq 2$

| $e$ | $G/e$ isomorphic to | $G/e$ is 3-conn.? | $G/e \in \tilde{G}$? |
|-----|-------------------|------------------|-----------------|
| spine edges | | | |
| $v_1v_n$ (plus edge) | $K_1 + P_{n-2}$ | no | no |
| $v_1 v_{n-i}$, $2 \leq i \leq r - 1$ | $G_{n-1,r-1,s}^{(+)} \backslash v_{n-i-1}v_{n-i}$ | no | no |
| $v_1 v_{n-1}$, $r \geq 3$ | $G_{n-1,r-1,s}^{+} \backslash v_{n-2}v_{n-1}$ | no | no |
| or $r = 2$ and $s = n - 4$ | | | |
| $v_1 v_{n-1}$, $r = 2$ and $s = n - 3$ | $G_{n-1,r-1,s}^{+} \backslash v_{n-4}v_{n-1}$ | yes | yes |
| $v_1 v_{n-r}$, $r + s = n - 2$ | $G_{n-1,r,s}^{+} \backslash v_{n-r-1}v_{n-r}$ | no | no |
| $v_1 v_{n-r}$, $r + s = n - 1, s \geq 3$ | $G_{n-1,r,s}^{+} \backslash v_{n-r-1}v_{n-r}$ | no | no |
| $v_1 v_{n-r}$, $r + s = n - 1, s = 2$ | $G_{n-1,r,s}^{+} \backslash v_{2}v_{3}$ | no | no |

Proof. Apply Lemma 2.4(i) repeatedly to replace contractions by deletions (details are left to the reader).

Lemma 2.6. If a 3-connected graph $H$ is a minor of a 3-connected graph $G$, then there is a sequence of 3-connected graphs $G_0, G_1, \ldots, G_k$ where $G_0 \cong G$, $G_k \cong H$, and each $G_{i+1}$ is obtained from $G_i$ by contraction or deletion of a single edge.

Proof. This follows from Seymour’s Splitter Theorem [13], or a similar result for graphs proved by Negami [11]. (Since we make our graphs simple after edge contractions, we do not need a special case for wheels.)

Corollary 2.7. If $H$ is a 3-connected minor of $G \in \tilde{G}$ then $H \in \tilde{G}$.

Proof. Take the 3-connected sequence $G \cong G_0, G_1, \ldots, G_k \cong H$ given by Lemma 2.6. From Lemmas 2.3 and 2.4(ii), if $G_i \in \tilde{G}$ then $G_{i+1} \in \tilde{G}$ also, and the result follows by induction.

2.2 Small cases

Figure 3 shows nine small graphs that are 3-connected (easily checked), not in $\tilde{G}$ (also easily checked; all but $D$ have a $K_{3,3}$ minor and so are nonplanar) and $K_{2,4}$-minor-free. The first graph, $K_5$, is the only 3-connected graph on fewer than six vertices that is not in $\tilde{G}$. To prove that the other eight graphs are $K_{2,4}$-minor-free we examine the two maximal graphs $C^+$ and $D$, and show that the rest are minors of $C^+$.

Lemma 2.8. The graph $C^+$ is $K_{2,4}$-minor-free.

Proof. Consider $C^+$ with vertices labeled as on the left in Figure 4. Suppose there is a standard $K_{2,4}$ minor $(R_1, R_2; S)$ in $C^+$ and suppose $|R_1| = 1$. Then $R_1$ must be either $v_4$ or $v_5$ since these are the only vertices of degree four. Say, without loss of generality, $R_1 = \{v_4\}$. Then $S = \{v_5, v_6, v_7, v_8\}$, and $R_2$ must be a subset of $\{v_1, v_2, v_3\}$. None of these three vertices are adjacent to $v_5$, however, so we cannot have $R_2$ adjacent to $v_5$ and thus we cannot have $|R_1| = 1$, or symmetrically $|R_2| = 1$. Thus $|R_1| \geq 2$ and $|R_2| \geq 2$ and since $|V(C^+)| = 8, |R_1| = |R_2| = 2$. 


Let $T$ be a triangle with a set $N$ of neighbors with $|N| = 3$. Suppose $R_1 \subseteq V(T)$. Then we would have $N \subseteq S$ along with the third vertex $t$ of $T$, but $N$ separates $t$ from the rest of the graph so $R_2$ cannot be adjacent to $t$. Thus $R_1$ (or symmetrically $R_2$) cannot consist of two vertices in a triangle with only three neighbors. In $C^+$, we have the following triples of vertices which form such triangles: $\{v_1, v_2, v_3\}$, $\{v_4, v_5, v_6\}$, $\{v_4, v_5, v_7\}$, and $\{v_4, v_5, v_8\}$. The only remaining pairs of adjacent vertices that could make up $R_1$ or $R_2$ are $\{v_3, v_6\}$, $\{v_2, v_8\}$, and $\{v_1, v_7\}$ where all three cases are symmetric. If $R_1 = \{v_3, v_6\}$, then $R_2$ must be $\{v_7, v_8\}$ but this set is not an option for $R_2$.

**Lemma 2.9.** The graph $D$ is $K_{2,4}$-minor-free.

*Proof.* It is easy to check that $D$ has no subgraph isomorphic to $K_{2,4}$, nor does $D/e$ for any $e \in E(D)$. Hence $D$ is $K_{2,4}$-minor-free since $|V(D)| = 7$.

Figure 4 shows what we will prove is the Hasse diagram for the the minor ordering of all 3-connected minors of $C^+$ (also labeled $K_2^+$, following Ding and Liu [5]) and $D$. For future reference the figure also includes three additional, circled graphs $Q_3$ (the cube), $Q_3/e$ (contract any edge of $Q_3$) and $V_8$ (the 8-vertex twisted cube or Möbius ladder). Unlike the other graphs, these three have $K_{2,4}$ minors, as shown by the minor in $Q_3/e$ on the right in Figure 6. Here, and later, a $K_{2,4}$ minor is indicated by two groups of vertices circled by dotted curves representing the two vertices in one part of the bipartition of $K_{2,4}$, and four triangular vertices representing the other part.

**Lemma 2.10.** Figure 4 is the Hasse diagram for all 3-connected minors (up to isomorphism) of $C^+$, $D$, $Q_3$ and $V_8$.

*Proof.* By Lemma 2.6 we can proceed by single edge deletions and contractions, and we do not need to consider further minors once we reach a graph that is not 3-connected. The figure is clearly correct for the 3-connected graphs on four or five vertices, so we consider only graphs with at least six vertices. Also, the 3-connected minors for graphs in $G$ follow from Lemmas 2.3 and 2.4(iii), so we consider only graphs not in $G$.

In what follows results of all deletions or contractions are identified only up to isomorphism. When we lose 3-connectivity, in all but one case there will be at least one vertex of degree two. We work upwards in the figure.
For the graphs $K_{3,3}$, $A$ and $A^+$ label the vertices consecutively along the top row then the bottom row in Figure 3. For $K_{3,3}$, deleting any edge loses 3-connectivity; contracting any edge results in $W_5$. For $A$, deleting $v_2v_3$ yields $K_{3,3}$, and deleting any other edge loses 3-connectivity. Contracting an edge incident with $v_1$ yields $K_{3,3}\setminus e$, contracting $v_2v_3$ loses 3-connectivity, and contracting any other edge incident with $v_2$ or $v_3$ yields $W_5$. For $A^+$, all edges are equivalent up to symmetry to one of $v_1v_4$, $v_1v_5$, $v_2v_3$ or $v_2v_5$. Deleting $v_1v_4$ or $v_1v_5$ loses 3-connectivity, deleting $v_2v_3$ gives $A$, and deleting $v_2v_5$ gives $G_{6,2,3}$. Contracting $v_1v_4$ gives $K_5$, contracting $v_1v_5$ gives $K_5\setminus e$, contracting $v_2v_3$ loses 3-connectivity, and contracting $v_2v_5$ yields $W_5$.

For $B$ and $B^+$ we redraw $B^+$ as on the left in Figure 6 and take $B = B^+ \setminus v_6v_7$. For $B$, deleting any edge loses 3-connectivity. Up to symmetry, there are five edge contractions to consider: $v_1v_2$, $v_1v_3$, $v_1v_4$, $v_3v_6$ and $v_4v_6$. Contracting $v_1v_2$ yields $K_{3,3}$, contracting $v_1v_3$ loses 3-connectivity, contracting $v_1v_4$ yields $A$, contracting $v_3v_6$ results in $W_6$, and contracting $v_4v_6$ gives $G_{6,2,3}$. For $B^+$, all edges are equivalent up to symmetry to six possibilities: $v_1v_2$, $v_1v_3$, $v_1v_4$, $v_3v_6$, $v_4v_6$ and $v_6v_7$. Deleting $v_1v_2$, $v_1v_3$, $v_1v_4$ or $v_4v_6$ loses 3-connectivity, deleting $v_3v_6$ yields $G_{7,2,3}$, and deleting $v_6v_7$ results in $B$. Contracting $v_1v_3$ or $v_4v_7$ loses 3-connectivity, contracting $v_1v_2$ results in $A$, contracting $v_1v_4$ yields $A^+$, contracting $v_3v_6$ gives $W_6$, and contracting $v_4v_6$ gives $G_{6,2,3}$.

For $C^+$ we label the vertices as on the left in Figure 4 and take $C = C^+ \setminus v_4v_5$. Deleting any edge of $C$ loses 3-connectivity. Up to symmetry, there are three edge contractions to consider: $v_1v_2$, $v_1v_7$ and $v_4v_6$. Contracting $v_1v_2$ loses 3-connectivity, contracting $v_1v_7$ results in $B$, and contracting $v_4v_6$ gives $G_{7,2,3}$. For $C^+$, deleting $v_4v_5$ yields $C$ and deleting any other edge loses 3-connectivity. Up to symmetry, there are four edge contractions of $C^+$ to consider: $v_1v_2$, $v_1v_7$, $v_4v_5$ and $v_4v_6$. Contracting $v_1v_2$ or $v_4v_5$ loses 3-connectivity, contracting $v_1v_7$ results in $B^+$, and contracting $v_4v_6$ gives $G_{7,2,3}$.

We label $D$ as on the right in Figure 4. Up to symmetry all edges are equivalent to one of four edges:
$v_1v_3$, $v_2v_4$, $v_5v_6$ and $v_6v_7$. Deleting $v_1v_3$ results in $G_{7,2,3}$, and deleting any of the other three edges loses 3-connectivity. Contracting $v_1v_3$ or $v_2v_4$ loses 3-connectivity, contracting $v_5v_6$ yields the triangular prism $G_{6,2,2}$, and contracting $v_6v_7$ results in $G_{6,2,3}$.

Finally, consider $Q_3/e, Q_3$, and $V_8$. Label $Q_3/e$ as shown on the right in Figure 3. Every edge in $Q_3/e$ is adjacent to a degree three vertex so deleting any edge loses 3-connectivity. Up to symmetry, there are four edge contractions to consider: $v_1v_2$, $v_3v_4$, $v_2v_6$ and $v_3v_7$. Contracting $v_3v_4$ loses 3-connectivity, and contracting $v_2v_6$ also loses 3-connectivity (without creating a vertex of degree two). Contracting $v_1v_2$ results in $G_{6,2,3}$, and contracting $v_3v_7$ yields $G_{6,2,2}$. In the cube $Q_3$ all edges are symmetric; deleting any edge loses 3-connectivity, and contracting any edge yields $Q_3/e$. We may take $V_8$ to be $C_8 = (v_1v_2 \ldots v_8)$ with added diagonals $v_iv_{i+4}$ for $1 \leq i \leq 4$. Deleting any edge loses 3-connectivity, contracting a $C_8$ edge results in $B$, and contracting a diagonal yields $Q_4/e$.

Considering the minors of $C^+$, we obtain the following.

**Corollary 2.11.** The graphs $C$, $B^+$, $B$, $A^+$, $A$, and $K_{3,3}$ are $K_{2,4}$-minor-free.

### 2.3 Characterization of 3-connected graphs

**Theorem 2.12.** Let $G$ be a 3-connected graph. Then $G$ is $K_{2,4}$-minor-free if and only if $G \in \mathcal{G}$ or $G$ is isomorphic to one of the nine small exceptions shown in Figure 3.

Our original proof of this theorem examined the structure of a 3-connected $K_{2,4}$-minor-free graph relative to a longest non-Hamilton cycle in the graph. We analyzed cases and either derived a contradiction with a longer non-Hamilton cycle or a $K_{2,4}$ minor, or found a desired graph. Recent results of Ding and Liu [5] allow us to give a shorter proof, which we present here.

First we give some definitions. Denote by Oct$\setminus e$ the graph obtained from the octahedron by removing one edge. A 3-\textit{sum} of two 3-connected graphs $G_1$ and $G_2$ is a graph $G$ obtained by identifying a triangle of $G_1$ with a triangle of $G_2$ and possibly deleting some of the edges of the common triangle as long as no degree two vertices are created. Any 2-cut in $G$ would lead to a 2-cut in either $G_1$ or $G_2$ so $G$ is 3-connected. An example is the graph $C^+$ which is a 3-sum of $K_5$ and a triangular prism. A common 3-\textit{sum} of three or more graphs is formed by specifying one triangle in each graph and identifying all as a single triangle called the common triangle; again edges of the common triangle may be deleted as long as no degree two vertices are created. Let $S$ be the set of all graphs formed by taking common 3-sums of wheels and triangular prisms. All graphs in $S$ are 3-connected. We use the following result due to Ding and Liu.

**Theorem 2.13** (Ding and Liu [5]). Up to isomorphism the family of 3-connected Oct$\setminus e$-minor-free graphs consists of graphs in $S$ and 3-connected minors of $V_8$, $Q_3$, and $C^+$.

**Proof of Theorem 2.12.** The results of subsections 2.1 and 2.2 give the reverse direction of the proof.

For the forward direction, Oct$\setminus e$ contains $K_{2,4}$ as a subgraph, so all 3-connected $K_{2,4}$-minor-free graphs must be Oct$\setminus e$-minor-free graphs as described in Theorem 2.13. We must decide which of those graphs are actually $K_{2,4}$-minor-free. By Lemma 2.10, Figure 5 gives all 3-connected minors of $V_8$, $Q_3$, and $C^+$ up to isomorphism. The $K_{2,4}$-minor-free ones are uncircled; all are in $\mathcal{G}$ or one of the nine small exceptions.

So we must determine which members of $S$ are $K_{2,4}$-minor-free. Any common 3-sum of four or more graphs has a $K_{3,4}$ minor (the three vertices of the common triangle form the part of size three) and hence a $K_{2,4}$ minor. Thus, we consider common 3-sums of at most three graphs, analyzed according to the numbers of wheels and prisms.

First consider a common 3-sum of three wheels, $W_k$, $W_\ell$, and $W_m$. For $k = \ell = 5$ and $m = 4$, since all vertices of $W_4 = K_4$ are equivalent, there are two ways up to symmetry to form a common 3-sum (disregarding the possible existence of the edges of the common triangle): the hubs of the two wheels are
either identified or not. Both result in a $K_{2,4}$ minor, as shown in the left and middle pictures of Figure 7. The dashed edges are the edges of the common triangle which may or may not be present in the common 3-sum. Since graphs with $k, \ell \geq 5$, and $m \geq 4$ have one of these two graphs as a minor, these graphs also have $K_{2,4}$ minors. Hence at most one of $k, \ell, m$ can be greater than 4. When $k = 6$, $\ell = m = 4$, there is again a $K_{2,4}$ minor, shown on the right in Figure 7. Graphs with $k > 6$ and $\ell = m = 4$ have this graph as a minor and hence also have a $K_{2,4}$ minor. For $k = 5$, $\ell = m = 4$, we have the graph shown on the left and middle in Figure 8. With at least one dashed edge of the common triangle, this graph is isomorphic to $B$. With no or one dashed edge, the graph is isomorphic to $K_{3,3}$ or $A$, respectively.

Next consider a common 3-sum of two wheels and a prism. If the wheels are $W_5$ and $W_4$, then all common 3-sums have the $K_{2,4}$ minor shown on the left in Figure 9. Any other combination of wheels gives this, and hence $K_{2,4}$, as a minor, unless both wheels are $W_4$. Then we have the graph shown on the right in Figure 9. With any dashed edge we have a $K_{2,4}$ minor, shown in the figure for $e_1$ and $e_2$. With no dashed edge, the graph is isomorphic to $C$.

Now consider a common 3-sum of two wheels $W_k$ and $W_\ell$. Suppose the hubs of the wheels are not identified, or $k = 4$ or $\ell = 4$. We have the graph shown on the left in Figure 10. At least one of the edges labeled $e_1$ and $e_2$ must be present in the common 3-sum to ensure there are no degree two vertices. Let $n = k + \ell - 3$. With $e_1$ and $e_2$, the graph is isomorphic to $G_{n,k-2,\ell-2}$. With $e_1$ (or symmetrically $e_2$), the graph is isomorphic to either $G_{n,k-3,\ell-2}$ or $G_{n,k-2,\ell-3}$. In all cases $e_3$ is the optional plus edge. The spine is shown in the figure as the thick, highlighted path. Hence we obtain graphs in $\tilde{G}$.

Now suppose that $k, \ell \geq 5$ and the hubs of $W_k$ and $W_\ell$ are identified in the common 3-sum. The graph with $k = \ell = 5$ appears on the right in Figure 10. With the edge labeled $e_1$, we have the $K_{2,4}$ minor shown,
and if \( k, \ell \geq 5 \) we get a similar minor. Without \( e_1 \), both \( e_2 \) and \( e_3 \) must be present to ensure there are no vertices of degree two, and the graph is isomorphic in the general case to \( W_{k+\ell-3} \in \bar{\mathcal{G}} \).

\[ \begin{array}{c}
e_1 \quad e_2 \quad e_3 \end{array} \]

Figure 10

Now consider a common 3-sum of two prisms and one wheel. For \( W_4 \) we have the graph on the left in Figure 11 with the \( K_{2,4} \) minor shown; for any larger wheel we get this graph, and hence \( K_{2,4} \), as a minor.

Next consider a common 3-sum of two or three prisms. For two prisms we have the graph on the right in Figure 11. At least two dashed edges are needed to prevent a degree two vertex and so we have the \( K_{2,4} \) minor shown. In a common 3-sum of three prisms, the dashed edges need not be present to ensure 3-connectivity. However, instead of using one of the dashed edges in the \( K_{2,4} \) minor as on the right in Figure 11 we can use a path between these two vertices through the third prism. Hence a similar \( K_{2,4} \) minor exists.

\[ \begin{array}{c}
e_1 \quad e_2 \quad e_3 \end{array} \]

Figure 11

Consider a common 3-sum of one wheel \( W_k \) and one prism; this is unique up to isomorphism. Figure 12 shows the graph for \( k = 5 \) on the left. At least one of the edges \( e_1 \) and \( e_2 \) must be present to prevent vertices of degree two so we have the \( K_{2,4} \) minor shown. For \( k \geq 6 \) there is a similar minor. The graph for \( k = 4 \) is shown on the right in Figure 12. At least two dashed edges must be present to prevent degree two vertices. With two or three dashed edges the graph is isomorphic to \( G_{7,3,2} \) or \( D \), respectively.

\[ \begin{array}{c}
e_1 \quad e_2 \end{array} \]

Figure 12

Finally, a common 3-sum of a single graph is \( W_k \cong G_{k,1,k-3}^+ \in \mathcal{G} \) or the triangular prism, isomorphic to \( G_{6,2,2} \in \mathcal{G} \).

In [5] Ding and Liu also prove the following result, where \( K_{3,3}^+ \) is the graph \( K_{3,3} \) with two additional edges added on the same side of the bipartition.

**Theorem 2.14** (Ding and Liu [5]). *The family of all 3-connected \( K_{3,3}^+ \)-minor-free graphs consists of 3-connected planar graphs and 3-connected minors of three small graphs on at most ten vertices.*
Because \( K_{2,4} \) is a subgraph of \( K_{3,3}^4 \), \( K_{2,4} \)-minor-free graphs must be a subset of the graphs described in Theorem 2.14. Combining this with Theorem 2.13, we conclude that all large enough \( K_{2,4} \)-minor-free graphs \( G \) must be planar (and so \( K_{3,3} \)-minor-free) members of \( S \), hence common 3-sums of at most two graphs, which reduces the work needed to conclude that \( G \in \tilde{G} \). The analysis required for small graphs is not simplified by using Theorem 2.14, however, so we provide the full analysis using only Theorem 2.13.

3 The 2-connected case

We begin this section by looking at how \( K_{2,t} \) minors interact with separations in a graph. We will mostly be concerned with 2-separations.

Lemma 3.1. Suppose \((H,J)\) is a 2-separation in a graph \( G \) with \( V(H) \cap V(J) = \{x,y\} \). If \( G \) contains a standard \( K_{2,t} \) minor \((R_1,R_2;S)\) with \( t \geq 3 \), then one of the following hold:

(i) there exists a \( K_{2,2} \) minor in \( H + xy \),
(ii) there exists a \( K_{2,t} \) minor in \( J + xy \), or
(iii) \( x \in R_1 \) and \( y \in R_2 \) (or vice versa).

Proof. Let \( H' = H - \{x,y\} \) and \( J' = J - \{x,y\} \). Assume (iii) does not hold, then \( \{x,y\} \cap R_i = \emptyset \) for at least one \( i \); we may suppose that \( \{x,y\} \cap R_2 = \emptyset \). Since \( R_2 \) induces a connected subgraph, this means that \( R_2 \subseteq V(H') \) or \( R_2 \subseteq V(J') \); without loss of generality we assume that \( R_2 \subseteq V(H') \). Then necessarily \( S \subseteq V(H) \), and so \((R_1 \cap V(H),R_2;S)\) is a standard \( K_{2,t} \) minor in \( H + xy \) and (i) holds.

By a \( K_{2,t} \) minor \((R_1,R_2;S)\) rooted at \( x \) and \( y \), we mean \( x \in R_1 \) and \( y \in R_2 \). If part (iii) of Lemma 3.1 holds, then the \( K_{2,t} \) minor splits into two minors, \( K_{2,t_1} \) and \( K_{2,t_2} \) with \( t_1 + t_2 = t \), both rooted at \( x \) and \( y \). For \( K_{2,4} \) minors this means that we will be concerned with rooted \( K_{2,2} \) minors; we will describe the structure of graphs without rooted \( K_{2,2} \) minors. Note that Demasi [3, Lemma 2.2.2] has characterized graphs without \( K_{2,2} \) minors rooted at all four vertices, in terms of disjoint paths.

An \( xy \)-outerplane embedding of a connected graph \( G \) with \( x,y \in V(G) \) is an embedding of \( G \) in a closed disk \( D \) such that a Hamilton \( xy \)-path \( P \) of \( G \) is contained in the boundary of \( D \). This is equivalent to embedding \( G \) in the plane so that the outer facial walk contains \( P \) as an uninterrupted subwalk, or so that all edges not in \( P \) lie ‘on the same side’ of \( P \); we use this as our practical definition. The path \( P \) is called the outer path. A graph is \( xy \)-outerplanar, or generically path-outerplanar, if it has an \( xy \)-outerplane embedding.

A block is a connected graph without a cutvertex: an isolated vertex, an edge, or a 2-connected graph. The blocks of a graph \( G \) are the maximal blocks that are subgraphs of \( G \). The block-cutvertex tree of a connected graph \( G \) is a tree whose vertices are the blocks and cutvertices of \( G \); a block \( B \) and cutvertex \( v \) are adjacent if \( v \in V(B) \).

The following useful properties are obvious, so we omit their proofs.

Lemma 3.2. (i) If \( G \) is \( xy \)-outerplanar, \( H \) is \( yz \)-outerplanar, and \( V(G) \cap V(H) = \{y\} \) then \( G \cup H \) is \( xz \)-outerplanar.

(ii) Suppose \( x \neq y \). Then \( G \) is \( xy \)-outerplanar if and only if \( G + xy \) is a block with an outerplane embedding in which \( xy \) is on the outer face. Such an embedding of \( G + xy \) is also \( xy \)-outerplane.

We now characterize rooted \( K_{2,2} \)-minor-free graphs.

Lemma 3.3. Suppose \( x \) and \( y \) are distinct vertices of \( G \) and \( G' = G + xy \) is a block. Then \( G \) has no \( K_{2,2} \) minor rooted at \( x \) and \( y \) if and only if \( G \) is \( xy \)-outerplanar.

Proof. (\( \Leftarrow \)) Assume an \( xy \)-outerplane embedding of \( G \). Add a vertex \( z \) and edges \( xz, yz \) to \( G \) in the outer face; the resulting graph \( G'' \) is outerplanar. If \( G \) has a \( K_{2,2} \) minor rooted at \( x \) and \( y \), then \( G'' \) has a \( K_{2,3} \) minor, which is a contradiction since outerplanar graphs are \( K_{2,3} \)-minor-free.
(⇒) Proceed by induction on \(|E(G)|\). The base case for \(G\) is \(K_2\) which has no \(K_{2,2}\) minor rooted at \(x\) and \(y\) and is clearly \(xy\)-outerplanar. Now assume the claim holds for all graphs on \(m \geq 1\) edges and suppose \(|E(G)| = m + 1\). Then \(G'\) is 2-connected.

First assume there is a cutvertex \(v\) in \(G\). Since \(G'\) is 2-connected, the block-cutvertex tree of \(G\) must be a path \(B_1v_1B_2v_2 \ldots v_{k-1}B_k\) where \(k \geq 2\), \(x \in V(B_1) - \{v_1\}\) and \(y \in V(B_k) - \{v_{k-1}\}\). Define \(v_0 = x\) and \(v_k = y\). Because \(G\) has no \(K_{2,2}\) minor rooted at \(x\) and \(y\), each block \(B_i\) has no \(K_{2,2}\) minor rooted at \(v_{i-1}\) and \(v_i\) for \(1 \leq i \leq k\). Thus, by induction each block \(B_i\) is \(v_{i-1}v_i\)-outerplanar. By Lemma 3.2(i), the outerplane embeddings of the blocks can then be combined to create an \(xy\)-outerplane embedding of \(G\), as in Figure 13.

![Figure 13](image)

Now suppose \(G\) has no cutvertex (\(G\) is 2-connected). Assume that \(G\) contains the edge \(xy\). Then by induction, \(G'\setminus xy\) has an \(xy\)-outerplane embedding. By Lemma 3.2(ii), \(G\) also has an \(xy\)-outerplane embedding. Therefore, we may assume that \(G\) does not contain the edge \(xy\). Since \(G\) has no cutvertex, there exist two internally disjoint \(xy\)-paths. Since \(xy \notin E(G)\), each path has an internal vertex, and hence they yield a \(K_{2,2}\) minor rooted at \(x\) and \(y\), a contradiction.

In order to describe the structure of 2-connected \(K_{2,4}\)-minor-free graphs, we need the following lemma:

**Lemma 3.4.** Suppose \(t \geq 3\). Let \(z\) be a degree two vertex in a graph \(G\) with neighbors \(x\) and \(y\). Let \(G'\) be the graph formed from \(G\) by replacing the path \(xy\) with an \(xy\)-outerplanar graph \(J\) on at least three vertices. Then \(G\) is \(K_{2,1}\)-minor-free if and only if \(G'\) is \(K_{2,1}\)-minor-free.

**Proof.** (⇐) \(G\) is a minor of \(G'\) so if \(G'\) is \(K_{2,1}\)-minor-free then so is \(G\).

(⇒) Let \(H = G - z\). Then \((H, J)\) is a 2-separation in \(G'\) with \(V(H) \cap V(J) = \{x, y\}\). Because \(G\) is \(K_{2,1}\)-minor-free, we know that \(H + xy\) is \(K_{2,1}\)-minor-free and also there is no \(K_{2,1}\)-minor in \(H\) rooted at \(x\) and \(y\). Because \(J + xy\) is outerplanar, \(J + xy\) is \(K_{2,1}\)-minor-free. Thus by Lemma 3.3, if \(G'\) has a \(K_{2,1}\) minor, then \(x \in R_1\) and \(y \in R_2\). If \(|S \cap V(J)| \geq 2\), then \(J\) has a \(K_{2,2}\) minor rooted at \(x\) and \(y\) which contradicts Lemma 3.3. Thus \(|S \cap V(H)| \geq t - 1\) but now we have a \(K_{2,1}\)-minor rooted at \(x\) and \(y\) in \(H\) which is a contradiction. Hence \(G'\) is \(K_{2,1}\)-minor-free.

We can now describe the structure of 2-connected \(K_{2,4}\)-minor-free graphs, using one new concept. If \(G\) is \(K_{2,4}\)-minor-free then \(F \subseteq E(G)\) is subdividable if the graph formed from \(G\) by subdividing all edges of \(F\) (replacing each edge by a path of length 2) is \(K_{2,4}\)-minor-free. The edge \(e\) is subdividable if \(\{e\}\) is subdividable. If \(F\) is a subdivisible set then every edge of \(F\) is subdividable, but the converse is not true.

**Theorem 3.5.** Let \(G\) be a block. Then \(G\) is \(K_{2,4}\)-minor-free if and only if one of the following holds.

(i) \(G\) is outerplanar;

(ii) \(G\) is the union of three \(xy\)-outerplanar graphs \(H_1, H_2, H_3\) and possibly the edge \(xy\), where \(|V(H_i)| \geq 3\) for each \(i\) and \(V(H_i) \cap V(H_j) = \{x, y\}\) for \(i \neq j\).

(iii) \(G\) is obtained from a 3-connected \(K_{2,4}\)-minor-free graph \(G_0\) by replacing each edge \(x_iy_i\) in a subdividable set of edges \(\{x_1y_1, x_2y_2, \ldots, x_ky_k\}\) by an \(x_iy_i\)-outerplanar graph \(H_i\), where \(V(H_i) \cap V(G_0) = \{x_i, y_i\}\) for each \(i\), and \(V(H_i) \cap V(H_j) \subseteq V(G_0)\) for \(i \neq j\).

**Proof.** (⇒) For (i), all outerplanar graphs are \(K_{2,4}\)-minor-free since they are \(K_{2,3}\)-minor-free. To show that a graph \(G\) in (ii) is \(K_{2,4}\)-minor-free, we use Lemma 3.4. \(G\) is \(K_{2,4}\)-minor-free if the graph formed from
G by replacing each of the three outerplanar pieces with a single vertex is $K_{2,4}$-minor-free. This graph is either $K_{2,3}$ or $K_{1,1,1,3}$ and is thus $K_{2,4}$-minor-free. We use Lemma 3.4 again to show that graphs in (iii) are $K_{2,4}$-minor-free. Let $G'$ be formed from a 3-connected $K_{2,4}$-minor-free graph by subdividing a subdividable set of edges. $G'$ is still $K_{2,4}$-minor-free by the definition of subdividable set. Now replace each subdivided edge $x_iy_i$ with an $x_iy_i$-outerplanar graph; by Lemma 3.4 the resulting graph is still $K_{2,4}$-minor-free.

(⇒) Suppose $G$ is a $K_{2,4}$-minor-free block. We proceed by induction on $n = |V(G)|$. As the basis, if $n ≤ 4$ then $G$ is one of $K_1$, $K_2$, $K_3$, $K_{1,1,2}$ or $C_4$, which are outerplanar and covered by (i), or $K_4$, which is 3-connected and covered by (iii). If $G$ is 3-connected then (iii) holds.

So we may assume that $n ≥ 5$ and $G$ has a 2-cut $\{x,y\}$. Let $H'_1, H'_2, \ldots, H'_4$, where $\ell ≥ 2$, be the components of $G - \{x,y\}$, and for each $i$ let $H_i$ be the subgraph induced by $V(H'_i) \cup \{x,y\}$.

If $\ell ≥ 4$, then $G$ has a $K_{2,4}$ minor with $x \in R_1$, $y \in R_2$, and $S$ consisting of a vertex from each of $H'_1, H'_2, H'_3, H'_4$. This is a contradiction.

Suppose $\ell = 3$. If some $H_i$ is not $xy$-outerplanar, then we have a $K_{2,4}$ minor: by Lemma 3.3 there is a $K_{2,2}$ minor rooted at $x$ and $y$ in $H_i$, to which we may add one vertex from each of the two other components of $G - \{x,y\}$. Thus, $H_1, H_2, H_3$ are all $xy$-outerplanar and (ii) holds.

Now suppose $\ell = 2$. If neither $H_1$ nor $H_2$ is $xy$-outerplanar, then $G$ contains a $K_{2,4}$ minor. If both are $xy$-outerplanar then $G$ is outerplanar as in (i). Hence one, say $H_1$, is not $xy$-outerplanar and the other, $H_2$, is $xy$-outerplanar. Let $H'_1 = H_1 + xy$. Since $|V(H'_1)| < |V(G)|$, by induction $H'_1$ is in (i), (ii), or (iii). By Lemma 3.2(ii), because $H_1$ is not $xy$-outerplanar, $H'_1$ is not outerplanar and hence not in (i). If $H'_1$ is in (ii), then the 2-cut $\{u,v\}$ in $H'_1$ giving three components is also a 2-cut in $G$ giving three components, and so, applying the argument for $\ell = 3$ to $\{u,v\}$, (ii) holds for $G$.

Now assume $H'_1$ is in (iii): $H'_1$ is a 3-connected $K_{2,4}$-minor-free graph $G_0$ with each edge $f = uv$ of a subdividable set $F$ replaced by a $uv$-outerplanar graph $J(f)$. Let $H'_2$ be $H_2 + xy$ if $xy \in E(G)$, and $H_2$ otherwise. In either case $H'_2$ is $xy$-outerplanar and $G$ is obtained from $H'_1$ by replacing $xy$ by $H'_2$.

Suppose first that $xy \notin \bigcup_{f \in F} E(J(f))$; then $xy \in E(G_0) - F$. If we let $J(xy) = H'_2$, then $G$ is obtained from $G_0$ by replacing each $f \in F \cup \{xy\}$ by $J(f)$. The graph obtained from $G$ by replacing every $J(f)$, $f \in F \cup \{xy\}$, by a path of length two with the same ends as $f$ is the same as the graph obtained from $G_0$ by subdividing every edge of $F \cup \{xy\}$. Since $G$ is $K_{2,4}$-minor-free, this graph is also $K_{2,4}$-minor-free by repeated application of Lemma 3.3, so $F \cup \{xy\}$ is subdividable in $G_0$. Hence (iii) holds for $G$.

Next suppose $xy$ is an edge of some $J(f)$, $f = uv \in F$, with outer path $P$. Suppose $xy \notin E(P)$. Then there is at least one vertex in the subpath $Q$ of $P$ between, but not including, $x$ and $y$. No vertex of $Q$ is adjacent to a vertex of $V(H'_1) - V(J(f))$ or, because $xy \in E(J(f))$, to a vertex of $V(J(f)) - (V(Q) \cup \{x,y\})$.

Now there exists $w \in V(H'_3) - V(J(f))$, and $Q$ and $w$ are in different components of $H'_1 - \{x,y\} = H'_1$, contradicting the fact that $H'_1$ is connected. So $xy \in E(P)$. Then the graph $J'(f)$ obtained by replacing $xy$ in $J(f)$ with the $xy$-outerplanar graph $H'_2$ is still $uv$-outerplanar. Thus $G$ is again in (iii).

To complete the 2-connected case, it remains to find all subdividable sets of edges in part (iii) of Theorem 3.5 for each 3-connected $K_{2,4}$-minor-free graph. If a set of edges is subdividable, then all subsets of that set are also subdividable, so it suffices to state the maximal (under inclusion) subdividable sets of edges in each graph. We start with graphs in $G$ with $n ≥ 6$. The graphs $G_{6,2,2}$, $G_{6,2,2}^+ \cong G_{6,2,3}$, and $G_{7,2,3}$ need special treatment and are dealt with later.

**Theorem 3.6.** Consider $G_{n,r,s}^{n+r} \in G$ with $r ≤ s$ and $n ≥ 6$. (Results for $r > s$ may be obtained using the isomorphism between $G_{n,r,s}^{n+r}$ and $G_{n,s,r}^{n+s}$.)

(i) When $r = 1$, the wheel $G_{n,1,n-3}^+$ has $n - 1$ maximal subdividable sets of edges. Each one includes all edges of the rim as well as one of the spokes.

(ii) When $r = 2$, $G_{n,2,s}$ with $s ≥ 4$ or $G_{n,2,s}^+$ with $s ≥ 3$ has two maximal subdividable sets of edges: the edge sets of the spine, $v_1v_2 \ldots v_n$, and second spine, $v_{n-2}v_{n-3} \ldots v_1v_{n-1}v_n$. 

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(iii) When \( r \geq 3 \) the only maximal subdividable set of edges is the edge set of the spine, \( v_1v_2\ldots v_n \).

**Proof.** We first show that each claimed subdividable set is subdividable. For the wheel \( G_{n,1,n-3}^+ \), subdividing all edges of the rim and one spoke gives a graph isomorphic to a subgraph of \( G_{2n,2,2n-4} \), and hence \( K_{2,4} \)-minor-free. For \( r \geq 2 \) the graph formed by subdividing all edges of the spine in \( G_{n,r}^{(+)} \) is isomorphic to a subgraph of another graph in \( G \) with \( 2n - 1 \) vertices, and thus \( K_{2,4}\)-minor-free. So the edge set of the spine is subdividable. When \( r = 2 \) the second spine is the image under an isomorphism of the spine in another (or possibly the same) member of \( G \), and hence the edge set of the second spine is also subdividable.

Now we show that the sets of edges listed are maximal and are the only subdividable sets. Begin with the wheel \( G_{n,1,n-3}^+ \). All edges of the rim are in each set so we consider the spokes. If we subdivide two adjacent spokes, we have the \( K_{2,4} \) minor shown on the left in Figure 14. A similar minor exists if we subdivide nonadjacent spokes as long as \( n \geq 6 \). Hence we cannot divide two spokes and the sets listed are maximal and are the only subdividable sets of edges.

![Figure 14](image1)

Now assume \( r, s \geq 2 \). For this portion of the proof, we remove the assumption that \( r \leq s \) (which is just for brevity in stating our results). Denote by \( G \circ e \) the graph formed from \( G \) by subdividing the edge \( e \). We consider subdivision of non-spine edges \( v_i v_{n-i} \) for \( 0 \leq i \leq r \); edges \( v_n v_{i+j} \) for \( 0 \leq j \leq s \) are handled by symmetry. The situations \( i = 0 \) and \( j = 0 \) correspond to a plus edge.

We describe two cases in which we can find a \( K_{2,4} \)-minor. The first, Case A, is the \( K_{2,4} \) minor in \( G_{5,2,2}^+ \circ v_1 v_5 \) shown on the right in Figure 14. If \( s \geq 2 \) and \( 0 \leq i \leq r - 2 \), then we form \( G_{5,2,2}^+ \circ v_1 v_5 \), and hence \( K_{2,4} \), as a minor from \( G_{n,r,s}^{(+)} \circ v_1 v_{n-i} \) by contracting all edges of the paths \( v_3 v_4 \ldots v_{n-i-2} \) and \( v_{n-i} v_{n-i+1} \ldots v_n \) and deleting multiple edges.

The second case, Case B, is the \( K_{2,4} \) minor in \( G_{5,2,2}^+ \circ v_1 v_3 \) shown on the left in Figure 15. Note that the minor does not use the edge \( v_2 v_5 \). As with Case A, this minor is inherited by the following larger graphs that have \( G_{5,2,2}^+ \circ v_1 v_3 \) as a minor:

(B1) \( G_{n,r,s}^+ \circ v_1 v_{n-i} \) with \( s \geq 2 \) and \( 2 \leq i \leq r \);

(B2) \( G_{n,r,s}^+ \circ v_1 v_{n-i} \) with \( s \geq 2 \) and \( 3 \leq i \leq r \); and

(B3) \( G_{n,r,s}^+ \circ v_1 v_{n-2} \) with \( s \geq 3 \).

For graphs in (B1), form \( G_{5,2,2}^+ \circ v_1 v_3 \) as a minor from \( G_{n,r,s}^+ \circ v_1 v_{n-i} \) by contracting all edges of the paths \( v_3 v_4 \ldots v_{n-i} \) and \( v_{n-i+1} v_{n-i+2} \ldots v_{n-1} \) and deleting multiple edges as well as the edge \( v_1 v_3 \) if it is present after contraction. Similarly for graphs in (B2), contract all edges of the paths \( v_3 v_4 \ldots v_{n-i} \) and \( v_{n-i+2} v_{n-i+3} \ldots v_n \) and delete multiple edges and \( v_1 v_3 \). For graphs in (B3), contract \( v_1 v_2 \) and all edges of the path \( v_4 v_5 \ldots v_{n-2} \) and delete multiple edges and \( v_1 v_3 \).

![Figure 15](image2)
For $G_{n,r,s}^{(+)}$ with $r, s \geq 3$, Case A shows that $v_1v_{n-r-2}, v_1v_{n-r-1}, \ldots, v_1v_{n-1}$ and (if present) $v_1v_n$ are not subdividable. Case B shows that $v_1v_{n-r}, v_1v_{n-r+1}, \ldots, v_1v_{n-2}$ are not subdividable. By symmetry all non-spine edges incident to $v_n$ are not subdividable, and hence the spine is the only maximal subdividable set of edges.

Now either $r = 2$ or $s = 2$. For our stated result we only need the case $r = 2$ with $s$ as in (ii). Consider $G_{n,2}^{(+)}$. Case A forbids subdivision of $v_1v_n$ (if present) and (B3) does the same for $v_1v_{n-2}$. Applying symmetry, Case A forbids subdivision of $v_nv_{1+j}$ for $1 \leq j \leq s-2$, and Case B covers $v_nv_{1+j}$ for $2 \leq j \leq s$ if there is a plus edge and $3 \leq j \leq s$ otherwise. The conditions in (ii) mean that these cover $v_nv_{1+j}$ for all $j$, $1 \leq j \leq s$. So the only possible subdividable non-spine edge is $v_1v_{n-1}$, which we already know is subdividable along with all edges of the spine other than $v_{n-2}v_{n-1}$, as this is the edge set of the second spine. So consider $v_1v_{n-1}$ and $v_{n-2}v_{n-1}$ together. We use the $K_2,4$ minor in $G_{6,2,2}^{(+)} \circ v_1v_5 \circ v_4v_5$ shown on the right in Figure 15. When $n \geq 6$, $G_{n,2}^{(+)} \circ v_1v_{n-1} \circ v_{n-2}v_{n-1}$ has $G_{6,2,2}^{(+)} \circ v_1v_5 \circ v_4v_5$, and hence $K_2,4$, as a minor: delete $v_nv_{1+j}$ with $j = 0$ (if present) and $3 \leq j \leq s$, then contract all edges of $v_4v_5 \ldots v_{n-2}$. Therefore $\{v_1v_{n-1}, v_{n-2}v_{n-1}\}$ is not subdividable, and the only maximal subdividable sets are the edge sets of the spine and second spine.

### Table 2

| Graph                                      | Maximal Subdividable Sets of Edges | Number of Symmetric Copies |
|--------------------------------------------|-----------------------------------|----------------------------|
| $K_4 = W_4$                                | ![Diagram](#)                      | 12                        |
| $W_5 ($\(\cong G_{5,2,2}\))$             | ![Diagram](#)                      | 4 of each                 |
| $G_{5,2,2}^{(+)} ($\(\cong K_5\backslash e\))$ | ![Diagram](#)                      | 6 of each                 |
| $G_{6,2,2}$                                | edge set of spine                 | 6                         |
| $G_{6,2,2}^{(+)} ($\(\cong G_{6,2,3}\))$ | edge set of spine in $G_{6,2,2}^{(+)}$ | spine: 1                  |
|                                            | edge set of second spine in $G_{6,2,2}^{(+)}$ | second spine: 2          |
| $G_{7,2,3}$                                | edge set of spine, edge set of second spine, $\{v_1v_2, v_4v_5, v_6v_7, v_3v_7\}$ | 1 of each                 |
| $K_5$                                      | $\emptyset$                      | 1                         |
| $A, K_{3,3}$                               | ![Diagram](#)                      | A: 1                      |
|                                            |                                   | $K_{3,3}$: 6              |
| $A^+$                                      | ![Diagram](#)                      | 1                         |
| $B, B^+$                                   | ![Diagram](#)                      | 1                         |
| $C, C^+$                                   | ![Diagram](#)                      | 1                         |
| $D$                                        | ![Diagram](#)                      | 3                         |

All remaining small graphs are covered by Table 2. Verifying these results is straightforward; complete
Proofs may be found in [9, Section 5.2]. These results were also confirmed by computer. The dashed edges in the table indicate edges present in one graph but not the other. For example, in the row for \( C \) and \( C^+ \), the dashed edge is present in \( C^+ \) but not \( C \).

**Lemma 3.7.** The maximal subdividable sets of edges for the nine small cases not in \( \mathcal{G} \) as well as \( K_4 = W_1 \), \( W_5 \cong G_{5,2,2} \), \( K_5 \setminus e \cong G_{5,2,2}^+ \), \( G_6,6,2 \), \( G_7,6,2 \cong G_{6,2,3} \) and \( G_7,7,2 \) are listed in Table 2.

As mentioned earlier, a graph \( G \) is \( K_{2,4} \)-minor-free if and only if each of its blocks is \( K_{2,4} \)-minor-free, so our overall result can now be stated as follows.

**Theorem 3.8** (Characterization of \( K_{2,4} \)-minor-free graphs). A graph is \( K_{2,4} \)-minor-free if and only if each of its blocks is described by Theorem 3.5 where for Theorem 3.5 (iii), the 3-connected graphs are given in Theorem 2.12 and the subdividable sets are described in Theorem 3.6 and Lemma 3.7.

As a final comment, we note that a theorem of Dieng and Gavoille mentioned earlier can be derived from our results. We state it and just outline a proof.

**Corollary 3.9** (Dieng and Gavoille, see [1 Théorème 3.2]). For every 2-connected \( K_{2,4} \)-minor-free graph \( G \) there is \( U \subseteq V(G) \) with \(|U| \leq 2 \) (\(|U| \leq 1 \) if \( G \) is planar) such that \( G - U \) is outerplanar.

**Sketch of proof.** Consider the structure of \( G \) as described in Theorem 3.5. If (i) holds no vertices need to be deleted, and if (ii) holds then one of \( x \) or \( y \) can be deleted. To verify the result when (iii) holds, it suffices to show that for every 3-connected \( K_{2,4} \)-minor-free \( G_0 \) and every maximal subdividable set of edges \( F \) in \( G_0 \), there is \( U \subseteq V(G_0) \) with \(|U| \leq 2 \) (\(|U| \leq 1 \) if \( G_0 \) is planar) so that \( G_0 - U \) has an outerplane embedding with all remaining edges of \( F \) (those not incident with \( U \)) on the outer face. If \( G_0 = G_{n,r,s}^{(+)} \in \mathcal{G} \) is covered by Theorem 3.6 then \( G_0 - v_n \) always works. The result must be checked for the small graphs in Table 2.

Dieng and Gavoille in fact showed that there is an \( O(n) \) time algorithm to find either a \( K_{2,4} \)-minor or a set \( U \) as in Corollary 3.9 in any \( n \)-vertex graph.

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