

## Matched Drawings of Planar Graphs

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### Abstract

A natural way to draw two planar graphs whose vertex sets are matched is to assign each matched pair a unique  $y$ -coordinate. In this paper we introduce the concept of such matched drawings, which is a relaxation of simultaneous geometric embeddings with mapping. We study which classes of graphs allow matched drawings and show that (i) two 3-connected planar graphs or a 3-connected planar graph and a tree may not be matched drawable, while (ii) two trees or a planar graph and a sufficiently restricted planar graph—such as an unlabeled level planar (ULP) graph or a graph of the family of “carousel graphs”—are always matched drawable.

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## 1 Introduction

The visual comparison of two graphs whose vertex sets are associated in some way requires drawings of these graphs that highlight their association in a clear manner. Drawings of this type are of use for various areas of computer science, including bio-informatics, web data mining, network analysis, and software engineering. Of course each drawing individually should be as clear as possible, using, for example, few bends and crossings. But, most importantly, the positions of associated vertices in the two drawings should be “close”. This makes it possible for the user to easily identify structurally identical and structurally different portions of the two graphs, or to maintain her “mental map” [19]. Structural changes between two graphs and their visualizations arise, for example, when collapsing or expanding clusters in clustered drawings [8], during the navigation of very large graphs with a topological window [7, 18], in the analysis of evolving networks [1, 16], and in dynamic graph drawing [3, 20, 21]. In all these scenarios the basic approach is to maintain the relative positions of associated vertices as much as possible to smoothly transform one graph into another. In this way changes can be captured more easily by the human eye.

Two positions are definitely “close” if they are identical. Hence a substantial research effort has recently been devoted to the problem of computing straight-line drawings of two graphs on the same set of points. More specifically, assume we are given two planar graphs  $G_1 = (V_1, E_1)$  and  $G_2 = (V_2, E_2)$  with  $|V_1| = |V_2|$ , together with a one-to-one mapping between their vertices. A *simultaneous geometric embedding with mapping* (introduced by Brass et al. in [4]) of  $G_1$  and  $G_2$  is a pair of straight-line planar drawings  $\Gamma_1$  and  $\Gamma_2$  of  $G_1$  and  $G_2$ , respectively, such that for any pair of matched vertices  $u \in V_1$  and  $v \in V_2$  the position of  $u$  in  $\Gamma_1$  is the same as the position of  $v$  in  $\Gamma_2$ . Unfortunately, only pairs of graphs belonging to restricted subclasses of planar graphs admit a simultaneous geometric embedding with mapping. Brass et al. [4] showed how to simultaneously embed pairs of paths, pairs of cycles, and pairs of caterpillars, but they also proved that a path and a graph or two outerplanar graphs may not admit this type of drawing. Geyer, Kaufmann, and Vrt’o [17] recently proved that even a pair of trees may not have a simultaneous geometric embedding with mapping. These negative results motivated the study of relaxations of simultaneous geometric embeddings. One possibility is to introduce bends along the edges [5, 9, 10, 14], another, to allow that the same vertex occupies different locations in the two drawings [2, 4, 15], introducing ambiguity in the mapping.

In this paper we consider a different interpretation of two positions being “close”. Instead of requiring that matched vertices occupy the same location, we assign each matched pair a unique  $y$ -coordinate. This enables the user to unambiguously identify pairs of matched vertices but, at the same time, leaves us more freedom to draw both graphs clearly. Specifically, let again  $G_1 = (V_1, E_1)$  and  $G_2 = (V_2, E_2)$  be two planar graphs with  $|V_1| = |V_2|$ .  $G_1$  and  $G_2$  are *matched* if there is a one-to-one mapping between  $V_1$  and  $V_2$ . If a vertex  $u \in V_1$  is matched with a vertex  $v \in V_2$  then we say that  $u$  is the *partner* of  $v$  and that  $v$  is the partner of  $u$ . A *matched drawing* of  $G_1$  and  $G_2$  is a pair of straight-line

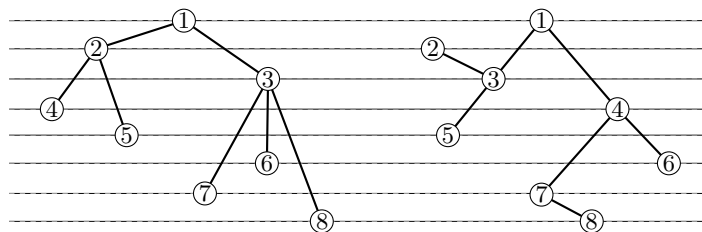


Figure 1: A matched drawing of two trees.

planar drawings  $\Gamma_1$  and  $\Gamma_2$  of  $G_1$  and  $G_2$ , respectively, such that for any pair of matched vertices  $u \in V_1$  and  $v \in V_2$  the  $y$ -coordinate of  $u$  in  $\Gamma_1$  is the same as the  $y$ -coordinate of  $v$  in  $\Gamma_2$ , and this  $y$ -coordinate is unique. If two matched graphs have a matched drawing, then we say that they are *matched drawable*. Matched drawings can be viewed as a relaxation of simultaneous geometric embedding with mapping. An example of a matched drawing of two trees is shown in Figure 1.

We remark that a problem similar to the matched drawability problem posed in this paper has been previously studied by Fernau et al. for the comparison of a pair of phylogenetic trees [12]. In that paper the matching is restricted to the set of leaves of the two trees, and the objective is to compute planar drawings for the two trees that minimize the number of crossings between the matching edges.

**Results and Organization.** We start by presenting pairs of graphs that are not matched drawable. In particular, in Section 2.1 we describe two isomorphic 3-connected planar graphs that both have 12 vertices and that are not matched drawable. We also present a 3-connected planar graph and a tree that both have 620 vertices and that are not matched drawable. This construction can be found in Section 2.2.

We continue by describing drawing algorithms for classes of graphs that are always matched drawable. In particular, in Section 3.1 we show that a planar graph and an unlabeled level planar (ULP) graph that are matched are always matched drawable. In Section 3.2 we extend these results to a planar graph and a graph of the family of “carousel graphs”. Finally, in Section 3.3 we prove that two matched trees are always matched drawable.

## 2 Graphs that are not Matched Drawable

### 2.1 Two 3-connected Graphs

We start by stating a simple property of planar straight-line drawings.

**Property 1** *Let  $G$  be an embedded planar graph and let  $\Gamma$  be a straight-line planar drawing of  $G$ . Let  $u$  be the vertex of  $G$  with the highest  $y$ -coordinate in*

$\Gamma$  and let  $v$  be the vertex of  $G$  with the lowest  $y$ -coordinate in  $\Gamma$ . Vertices  $u$  and  $v$  belong to the external face of  $G$ .

Now assume that  $G_1$  and  $G_2$  are two matched graphs with the following properties: (i)  $G_1$  contains two vertex-disjoint simple cycles  $C_1 = \{u_1, \dots, u_n\}$  and  $C'_1 = \{u'_1, \dots, u'_m\}$ , (ii)  $G_2$  contains two vertex-disjoint simple cycles  $C_2 = \{v_1, \dots, v_n\}$  and  $C'_2 = \{v'_1, \dots, v'_m\}$ , and (iii)  $u_i$  is the partner of  $v_i$  ( $1 \leq i \leq n$ ) and  $u'_j$  is the partner of  $v'_j$  ( $1 \leq j \leq m$ ). If  $\Psi_1$  is a planar embedding of  $G_1$  such that  $C'_1$  is inside  $C_1$  and if  $\Psi_2$  is a planar embedding of  $G_2$  such that  $C_2$  is inside  $C'_2$ , then we call  $\Psi_1$  and  $\Psi_2$  *interlaced embeddings* and  $C_1, C'_1, C_2$ , and  $C'_2$  *interlaced cycles*.

**Lemma 1** *Let  $G_1$  and  $G_2$  be two matched graphs with interlaced embeddings  $\Psi_1$  and  $\Psi_2$ . There is no matched drawing  $\Gamma_1$  and  $\Gamma_2$  of  $G_1$  and  $G_2$  such that  $\Gamma_1$  preserves  $\Psi_1$  and  $\Gamma_2$  preserves  $\Psi_2$ .*

**Proof:** Denote by  $C_1, C'_1, C_2$ , and  $C'_2$  the interlaced cycles of  $\Psi_1$  and  $\Psi_2$ . Suppose by contradiction that  $\Gamma_1$  and  $\Gamma_2$  exist. Denote by  $\overline{\Gamma}_1$  the subdrawing of  $\Gamma_1$  restricted to the subgraph  $C_1 \cup C'_1$  and by  $\overline{\Gamma}_2$  the subdrawing of  $\Gamma_2$  restricted to the subgraph  $C_2 \cup C'_2$ .

Since in  $\Psi_1$  cycle  $C'_1$  is inside cycle  $C_1$ , by Property 1 the top-most and the bottom-most vertices of  $\overline{\Gamma}_1$  belong to  $C_1$ ; denote these two vertices by  $u_t$  and  $u_b$ . Since  $\overline{\Gamma}_1$  is planar and since the drawing of  $C'_1$  is completely inside the drawing of  $C_1$ , every vertex  $u'_j$  of  $C'_1$  has a  $y$ -coordinate that is greater than the  $y$ -coordinate of  $u_b$  and smaller than the  $y$ -coordinate of  $u_t$ . Since  $\Gamma_1$  and  $\Gamma_2$  are matched drawings, every vertex  $v'_j$  of  $C'_2$  in  $\overline{\Gamma}_2$  has a  $y$ -coordinate that is greater than the  $y$ -coordinate of  $v_b$  (i.e., the partner of  $u_b$ ) and smaller than the  $y$ -coordinate of  $v_t$  (i.e., the partner of  $u_t$ ). However, since in  $\Psi_2$  cycle  $C_2$  is inside cycle  $C'_2$ , by Property 1 the top-most and the bottom-most vertices of  $\overline{\Gamma}_2$  belong to  $C'_2$ , a contradiction.  $\square$

**Theorem 1** *There exist two 3-connected planar graphs that are not matched drawable.*

**Proof:** Consider the two 3-connected planar graphs  $G_1$  and  $G_2$  in Figure 2. The partner of a vertex of  $G_1$  is any vertex in  $G_2$  that has the same label. To prove that  $G_1$  and  $G_2$  are not matched drawable, we show that all planar embeddings of  $G_1$  and  $G_2$  are interlaced embeddings.

Since  $G_1$  and  $G_2$  are 3-connected graphs, all their planar embeddings differ only in the choice of the external face. In  $G_1$  and  $G_2$  we can have five possible types of external face, depending on the labels of the vertices of such a face. Namely, an external face of  $G_1$  can have vertices with labels in one of these sets:  $\{a\}$ ,  $\{a, b\}$ ,  $\{b, c\}$ ,  $\{c, d\}$ ,  $\{d\}$ , while an external face of  $G_2$  can have vertices with labels in one of these sets:  $\{c\}$ ,  $\{c, d\}$ ,  $\{d, a\}$ ,  $\{a, b\}$ ,  $\{b\}$ . For any label  $\ell \in \{a, b, c, d\}$ , let  $C_{1,\ell}$  and  $C_{2,\ell}$  denote the three-cycles formed by the vertices with label  $\ell$  in  $G_1$  and in  $G_2$ , respectively. For any pair of external faces in  $G_1$  and  $G_2$  there are two distinct labels  $\ell, \ell' \in \{a, b, c, d\}$  such that  $C_{1,\ell'}$  is inside

$C_{1,\ell}$  in  $G_1$  and  $C_{2,\ell}$  is inside  $C_{2,\ell'}$  in  $G_2$ . Table 1(a) shows the inclusion relations between the three-cycles of  $G_1$  for each type of external face, where we use the notation  $\ell \succ \ell'$  to denote that cycle  $C_{1,\ell}$  is inside  $C_{1,\ell'}$ . Table 1(b) shows the inclusions between the three-cycles of  $G_2$ .

For each pair of external faces of  $G_1$  and  $G_2$ , Table 2 shows two labels  $\ell, \ell'$  such that  $C_{1,\ell}, C_{1,\ell'}, C_{2,\ell}, C_{2,\ell'}$  are interlaced cycles. More precisely, in Table 2 the rows are the labels of the external face of  $G_1$ , the columns are the labels of the external face of  $G_2$ , and in each cell two labels  $\ell, \ell'$  are shown such that  $\ell \succ \ell'$  in  $G_1$  and  $\ell' \succ \ell$  in  $G_2$ . For example, if the external face of  $G_1$  is the three-cycle  $C_{1,a}$  and if the external face of  $G_2$  is the three-cycle  $C_{2,b}$ , we have that in  $G_1$  cycle  $C_{1,d}$  is inside  $C_{1,c}$ , while in  $G_2$  cycle  $C_{2,c}$  is inside  $C_{2,d}$ . Hence, any pair of planar embeddings of  $G_1$  and  $G_2$  is a pair of interlaced embeddings.  $\square$

## 2.2 A 3-connected Graph and a Tree

The two graphs described in Theorem 1 are both 3-connected. Hence the question arises if two planar graphs, at least one of which is not 3-connected, are always matched drawable. This is unfortunately not the case: in the following we present a planar graph and a tree that are not matched drawable.

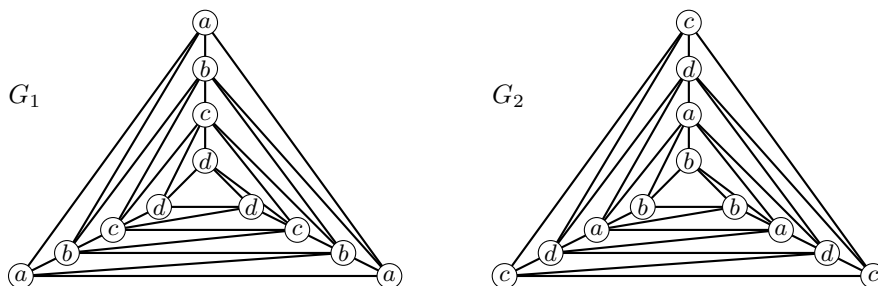


Figure 2: Two 3-connected planar graphs that are not matched drawable. The partner of a vertex of  $G_1$  is any vertex in  $G_2$  that has the same label.

<i>Ext. face labels</i>	<i>Incl. of cycles</i>	<i>Ext. face labels</i>	<i>Incl. of cycles</i>
{a}	$a \succ b \succ c \succ d$	{c}	$c \succ d \succ a \succ b$
{a, b}	$b \succ c \succ d$	{c, d}	$d \succ a \succ b$
{b, c}	$b \succ a; c \succ d$	{d, a}	$d \succ c; a \succ b$
{c, d}	$c \succ b \succ a$	{a, b}	$a \succ d \succ c$
{d}	$d \succ c \succ b \succ a$	{b}	$b \succ a \succ d \succ c$

(a)

(b)

Table 1: Inclusions between the three-cycles of  $G_1$  (table (a)) and of  $G_2$  (table (b)).

	{c}	{c, d}	{d, a}	{a, b}	{b}
{a}	a, c	a, c	c, d	c, d	c, d
{a, b}	b, d	b, d	c, d	c, d	c, d
{b, c}	b, a	b, a	b, a	c, d	c, d
{c, d}	b, a	b, a	b, a	c, a	c, a
{d}	b, a	b, a	b, a	d, a	d, a

Table 2: Interlaced cycles for each pair of external faces. The rows are the labels in the external face of  $G_1$ ; the columns are the labels in the external face of  $G_2$ . In each cell two labels  $\ell, \ell'$  are shown such that  $\ell \succ \ell'$  in  $G_1$  and  $\ell' \succ \ell$  in  $G_2$ .

Given a vertex  $v$  of a graph  $G$  and a drawing  $\Gamma$  of  $G$ , we denote by  $x(v)$  and  $y(v)$  the  $x$ - and  $y$ -coordinate of  $v$  in  $\Gamma$ . Let  $T^* = (V^*, E^*)$  be the tree depicted in Figure 3. Estrella-Balderrama et al. [11] proved the following lemma:

**Lemma 2 (Estrella-Balderrama et al. [11])** *Let  $T^*$  be the tree depicted in Figure 3. A straight-line planar drawing  $\Gamma$  of  $T^*$  such that  $y(v_0) < y(v_7) < y(v_3) < y(v_2) < y(v_4) < y(v_1) < y(v_5) < y(v_6)$  in  $\Gamma$  does not exist.*

Let  $T^*$  be rooted at vertex  $v_0$ , and for each vertex  $v_i$ , denote by  $d(v_i)$  the graph-theoretic distance of  $v_i$  from the root ( $i = 0, 1, \dots, 7$ ). We construct a tree  $T$  by using  $T^*$  as a model. See Figure 4 for an illustration.  $T$  has  $3^{d(v_i)}$  copies of each vertex  $v_i$  ( $i = 0, 1, \dots, 7$ ). The  $3^{d(v_i)}$  copies of  $v_i$  are denoted as  $v_{i,0}, v_{i,1}, \dots, v_{i,3^{d(v_i)}-1}$ . Vertex  $v_{h,k}$  is a child of vertex  $v_{i,j}$  in  $T$  if and only if  $v_h$  is a child of  $v_i$  in  $T^*$  and  $j = \lfloor k/3 \rfloor$  ( $0 \leq i, h \leq 7$ ), ( $0 \leq j \leq 3^{d(v_i)} - 1$ ), ( $0 \leq k \leq 3^{d(v_h)} - 1$ ). So  $T$  has one copy of  $v_0$  whose children are the three copies  $v_{1,0}, v_{1,1}$ , and  $v_{1,2}$  of  $v_1$ . The children of each copy of  $v_1$  are three of the nine copies of  $v_2$ , and so on. Three vertices of  $T$  with the same parent are called a *triplet* of  $T$ . The total number of vertices of  $T$  is 310.

The tree  $T$  is matched with a *nested-triangles graph*, which is defined as follows. A single vertex  $v$  is a nested-triangles graph denoted by  $G_0$ . A trian-

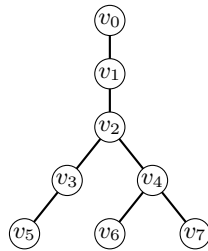


Figure 3: A tree that does not have a straight-line planar drawing with  $y(v_0) < y(v_7) < y(v_3) < y(v_2) < y(v_4) < y(v_1) < y(v_5) < y(v_6)$  [11].

vertex	copies	triplets	levels
$v_0$	1	0	0
$v_7$	81	27	1...27
$v_3$	27	9	28...36
$v_2$	9	3	37...39
$v_4$	27	9	40...48
$v_1$	3	1	49
$v_5$	81	27	50...76
$v_6$	81	27	77...103

Table 3: Matching between the vertices of  $T$  and the vertices of  $G_{103}$ .

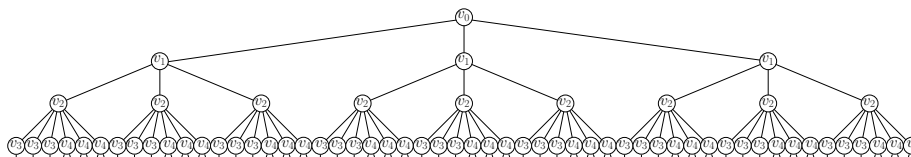


Figure 4: Tree  $T$  of the construction. Nodes of the last level (i.e. copies of nodes  $v_5$ ,  $v_6$ , and  $v_7$ ) are not shown.

gulated planar embedded graph  $G_k$  ( $k > 0$ ) is a nested-triangles graph if the external face of  $G_k$  has exactly three vertices and the graph  $G_{k-1}$ , obtained by removing the vertices on the external face, is still a nested-triangles graph. A levelling of the vertices is naturally defined for the vertices of  $G_k$ : level  $i$  of  $G_k$  contains the vertices that are on the external face of  $G_i$  ( $i = 0, 1, \dots, k$ ). Note that  $G_k$  has  $3k + 1$  vertices and  $k + 1$  levels. Thus,  $G_{103}$  has 310 vertices and 104 levels.

$T$  and  $G_{103}$  are matched in the following way. Vertex  $v_0$  is mapped to the (only) vertex of level 0. Each triplet of  $T$  is mapped to three vertices of  $G_{103}$  such that the level of these three vertices is the same in  $G_{103}$ . Also, all triplets formed by vertices that are copies of the same vertex of  $T^*$  are mapped to consecutive levels of  $G_{103}$ . The exact mapping is described in Table 3. Each row of the table refers to a different vertex of  $T^*$  and shows the number of copies of that vertex in  $T$ , the number of triplets in  $T$ , and the levels of  $G_{103}$  to which these triplets are mapped (a triplet for each level).

We now prove that, with the mapping described by Table 3,  $T$  and  $G_{103}$  are not matched drawable if we insist that the drawing of  $G_{103}$  preserves the embedding of  $G_{103}$ . We start with a useful property.

**Property 2** *Let  $\Gamma_{G_{103}}$  be any planar straight-line drawing of  $G_{103}$  that preserves the embedding of  $G_{103}$ . For each level  $i$  ( $0 \leq i \leq 103$ ) there exists a vertex of level  $i$  that has  $y$ -coordinate greater than the  $y$ -coordinates of all the vertices having level less than  $i$ .*

**Lemma 3** *A matched drawing  $\Gamma_T$  and  $\Gamma_{G_{103}}$  of the tree  $T$  and the graph  $G_{103}$  such that  $\Gamma_{G_{103}}$  preserves the embedding of  $G_{103}$  does not exist.*

**Proof:** Let  $\Gamma_{G_{103}}$  be any planar straight-line drawing of  $G_{103}$  that preserves the embedding of  $G_{103}$ . By exploiting Property 2, we can show that  $\Gamma_{G_{103}}$  induces an ordering  $\lambda$  of the vertices of  $T$  along the  $y$ -direction such that there exists a subtree  $T'$  of  $T$  isomorphic to  $T^*$  for which the ordering  $\lambda$  restricted to the vertices of  $T'$  is the ordering given in Lemma 2. This implies that  $T'$  (and hence  $T$ ) does not have a planar straight-line drawing that respects the ordering induced by  $\Gamma_{G_{103}}$ .

Denote by  $V_i$  the set of vertices of  $T$  that are copies of a vertex  $v_i \in T^*$  ( $i = 0, 1, \dots, 7$ ). We define subtree  $T'$  as follows.  $T'$  consists of eight vertices  $\bar{v}_0, \bar{v}_1, \dots, \bar{v}_8$ , where  $\bar{v}_i \in V_i$ . Of course,  $\bar{v}_0 = v_0$ . Vertex  $\bar{v}_i$  is a vertex  $v_{i,j}$  of  $V_i$

such that: (i) the parent of  $v_{i,j}$  is in  $T'$ , in particular, it is  $\bar{v}_{\lfloor j/3 \rfloor}$ ; and (ii)  $v_{i,j}$  is the vertex of its level for which Property 2 holds. Notice that the isomorphism between  $T'$  and  $T^*$  is guaranteed by the fact that there is one vertex for each set  $V_i$  and that a vertex is selected only if its parent is also selected.

We write  $V_i < V_j$  if all levels containing vertices of  $V_i$  are inside levels containing vertices of  $V_j$  in the embedding of  $G_{103}$ . Based on the mapping given in Table 3 we have that  $V_0 < V_7 < V_3 < V_2 < V_4 < V_1 < V_5 < V_6$ . This along with the fact that for each selected vertex Property 2 holds, implies that  $y(\bar{v}_0) < y(\bar{v}_7) < y(\bar{v}_3) < y(\bar{v}_2) < y(\bar{v}_4) < y(\bar{v}_1) < y(\bar{v}_5) < y(\bar{v}_6)$ . But by Lemma 2,  $T'$  does not admit a planar straight-line drawing such that the ordering of the vertices along the  $y$ -direction is the one given above.  $\square$

According to Lemma 3,  $T$  and  $G_{103}$  are not matched drawable in the case that one wants a drawing of  $G_{103}$  that preserves the embedding of  $G_{103}$ . In the following theorem we show that  $T$  and  $G_{103}$  can be used to construct a new tree and a new 3-connected planar graph that are not matched drawable even if we allow the embedding to be changed.

**Theorem 2** *There exist a tree and a 3-connected planar graph that are not matched drawable.*

**Proof:** Let  $\bar{T}$  be a tree that consists of two copies of  $T$  whose roots are adjacent. Let  $G$  be a graph obtained by taking two distinct copies of  $G_{103}$  and connecting the vertices of their external faces in such a way that the obtained graph is a triangulated planar graph. Denote as  $T'$  and  $T''$  the two copies of  $T$  that form  $\bar{T}$  and as  $G'_{103}$  and  $G''_{103}$  the two copies of  $G_{103}$  that form  $G$ . Also, define a mapping between  $\bar{T}$  and  $G$  such that the vertices of  $T'$  are mapped to the vertices of  $G'_{103}$  according to the mapping defined by Table 3, and the vertices of  $T''$  are mapped to the vertices of  $G''_{103}$  according to the mapping defined by Table 3. Since  $G$  is triangulated, it has a unique planar embedding except for the choice of the external face. Whatever face of  $G$  is chosen as the external one, the resulting embedding of  $G$  is such that either the embedding of  $G'_{103}$  or the embedding of  $G''_{103}$  is preserved. Thus either  $T'$  and  $G'_{103}$ , or  $T''$  and  $G''_{103}$  are in the condition of Lemma 3 and therefore are not matched drawable.  $\square$

### 3 Matched Drawable Graphs

In this section we describe drawing algorithms for classes of graphs that are always matched drawable. In particular, in Section 3.1 we show that a planar graph and an unlabeled level planar (ULP) graph that are matched are always matched drawable. In Section 3.2 we extend these results to a planar graph and a graph of the family of “carousel graphs”. Finally, in Section 3.3 we prove that two matched trees are always matched drawable.

These results show that matched drawings do indeed allow larger classes of graphs to be drawn than simultaneous geometric embeddings with mapping (a path and a planar graph may not admit a simultaneous geometric embedding with mapping [4] and the same negative result also holds for pairs of trees [17]).



### 3.1 Planar Graphs and ULP Graphs

ULP graphs were defined by Estrella-Balderrama, Fowler, and Kobourov [11]. Let  $G$  be a planar graph with  $n$  vertices. A  $y$ -assignment of the vertices of  $G$  is a one-to-one mapping  $\lambda : V \rightarrow \mathbb{N}$ . A *drawing of  $G$  compatible with  $\lambda$*  is a planar straight-line drawing of  $G$  such that  $y(v) = \lambda(v)$  for each vertex  $v \in V$ . A planar graph  $G$  is *unlabeled level planar* (ULP) if for any given  $y$ -assignment  $\lambda$  of its vertices,  $G$  admits a drawing compatible with  $\lambda$ .

**Theorem 3** *A planar graph and an ULP graph are always matched drawable.*

**Proof:** Let  $G_1$  be a planar graph and let  $G_2$  be an ULP graph. Compute a planar straight-line drawing of  $G_1$  such that each vertex has a different  $y$ -coordinate, for example with a slight variant of the algorithm of de Fraysseix, Pach, and Pollack [6]. The drawing of  $G_1$  together with the mapping between  $G_1$  and  $G_2$  defines a  $y$ -assignment  $\lambda$  for  $G_2$ . Since  $G_2$  is ULP it admits a drawing compatible with  $\lambda$ . It follows that  $G_1$  and  $G_2$  are matched drawable.  $\square$

ULP trees are characterized in [11]. A complete characterization of ULP graphs is given in [13]. A planar graph is ULP if and only if it is either a *generalized caterpillar*, or a *radius-2 star*, or a *generalized degree-3 spider*. These graphs are defined as follows (see also [13]). A graph is a *caterpillar* if deleting all vertices of degree one produces a path, which is called the *spine* of the caterpillar. A *generalized caterpillar* is a graph that contains cycles of length at most 4 in which every spanning tree is a caterpillar such that no three cut vertices are pairwise adjacent and no pair of adjacent cut vertices belong to the same 4-cycle. A *radius-2 star* is a  $K_{1,k}$ ,  $k > 2$ , in which every edge is subdivided at most once. The only vertex of degree  $k$  is called the *center* of the star. A *degree-3 spider* is an arbitrary subdivision of  $K_{1,3}$ . A *generalized degree-3 spider* is a graph with maximum degree 3 in which every spanning tree is either a path or a degree-3 spider.

**Corollary 4** *Let  $G_1$  and  $G_2$  be two matched graphs such that  $G_1$  is a planar graph and  $G_2$  is either a generalized caterpillar, or a radius-2 star, or a generalized degree-3 spider. Then  $G_1$  and  $G_2$  are matched drawable.*

### 3.2 Planar Graphs and Carousel Graphs

In this section we extend the result of Theorem 3 by describing a family of graphs that also includes non-ULP graphs and whose members have a matched drawing with any planar graph. Let  $G$  be a planar graph, let  $v$  be a vertex of  $G$ , and let  $\Gamma$  be a planar straight-line drawing of  $G$ .  $\Gamma$  is  *$v$ -stretchable* if: (i) there is a vertical ray from  $v$  going to  $+\infty$  that does not intersect any edge of  $\Gamma$ , and (ii) for any given  $\Delta > 0$ , there exists a value  $\Delta' \geq \Delta$  such that the drawing obtained by translating each vertex  $u$  with  $x(u) \geq x(v)$  to point  $(x(u) + \Delta', y(u))$  is still planar. Graph  $G$  is ULP  *$v$ -stretchable* if for every given  $y$ -assignment  $\lambda$  of its vertices,  $G$  admits a  $v$ -stretchable drawing compatible with  $\lambda$ . For example, the graph  $G$  shown in Figure 5(a) is ULP [13]. Furthermore, it is easy to see that

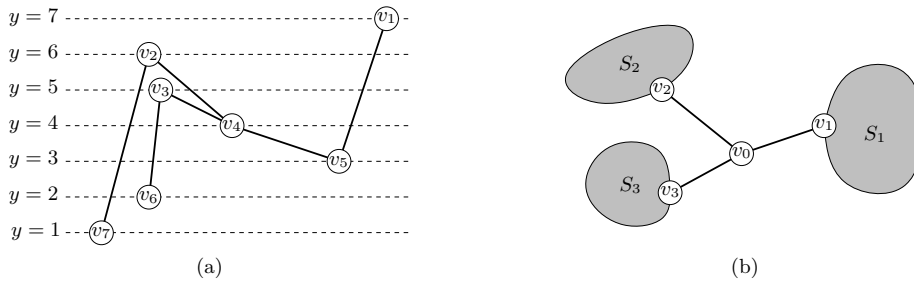


Figure 5: (a) A ULP graph which is ULP  $v_4$ -stretchable but not ULP  $v_3$ -stretchable. (b) A carousel graph.

for any possible  $y$ -assignment,  $G$  admits a  $v_4$ -stretchable drawing, and therefore  $G$  is ULP  $v_4$ -stretchable. On the other hand, for the  $y$ -assignment shown in Figure 5(a),  $G$  does not admit a drawing that is  $v_3$ -stretchable. Namely, in order to make  $v_3$  visible from vertically above, the path from  $v_6$  to  $v_4$  must cross the path from  $v_7$  to  $v_4$  or the path from  $v_1$  to  $v_4$ , or the paths from  $v_1$  to  $v_4$  and  $v_7$  to  $v_4$  must cross. Thus,  $G$  is not ULP  $v_3$ -stretchable.

A *carousel graph* is a connected planar graph  $G$  consisting of a vertex  $v_0$ , called the *pivot* of  $G$ , and of a set of disjoint subgraphs  $S_1, \dots, S_k$  ( $k > 1$ ) such that each  $S_i$  has a single vertex  $v_i$  adjacent to  $v_0$  ( $i = 1, \dots, k$ ) and  $S_i$  is ULP  $v_i$ -stretchable. Each subgraph  $S_i$  is called a *seat* of  $G$ . Vertex  $v_i$  is called the *hook* of  $S_i$ . Figure 5(b) illustrates the definition of a carousel graph.

**Theorem 5** *Any planar graph and any carousel graph that are matched are matched drawable.*

**Proof:** Let  $G_1$  be a planar graph and let  $G_2$  be a carousel graph. Let  $v_0$  be the pivot of  $G_2$  and let  $u$  be the partner of  $v_0$  in  $G_1$ . Compute a planar straight-line drawing  $\Gamma_1$  of  $G_1$  such that all vertices have different  $y$ -coordinates and  $u$  has the largest  $y$ -coordinate. Drawing  $\Gamma_1$  together with the mapping between  $G_1$  and  $G_2$  defines a  $y$ -assignment  $\lambda$  for the vertices in a drawing  $\Gamma_2$  of  $G_2$ . Clearly  $\lambda(w) < \lambda(v_0) = y_M$  for all vertices  $w \neq v_0$  of  $G_2$ .

In the following we describe an incremental method to compute a drawing  $\Gamma_2$  compatible with  $\lambda$ . Let  $S_1, \dots, S_k$  ( $k > 1$ ) be the seats of  $G_2$  and let  $v_i$  be the hook of  $S_i$  ( $1 \leq i \leq k$ ). Let  $\lambda_i$  be the  $y$ -assignment of the vertices of  $S_i$  induced by  $\lambda$ . As a preliminary step we compute a drawing  $\Sigma_i$  for each  $S_i$  that is compatible with  $\lambda_i$  and that is  $v_i$ -stretchable. Such a drawing exists because  $S_i$  is ULP  $v_i$ -stretchable. We further assume that the distance between any two different  $x$ -coordinates is at least 1 unit.

We incrementally construct  $\Gamma_2$  in  $k + 1$  steps. Denote by  $\Gamma_{2,i}$  the partial drawing of  $G_2$  obtained at the end of step  $i$  ( $0 \leq i \leq k$ ).  $\Gamma_{2,0}$  just consists of vertex  $v_0$  placed at position  $(0, y_M)$ . Drawing  $\Gamma_{2,i}$  is constructed from  $\Gamma_{2,i-1}$  by adding  $\Sigma_i$  at a suitable  $x$ -location and possibly translating some of its vertices further in  $x$ -direction (see Figure 6). Hence the resulting drawing  $\Gamma_{2,i}$  respects

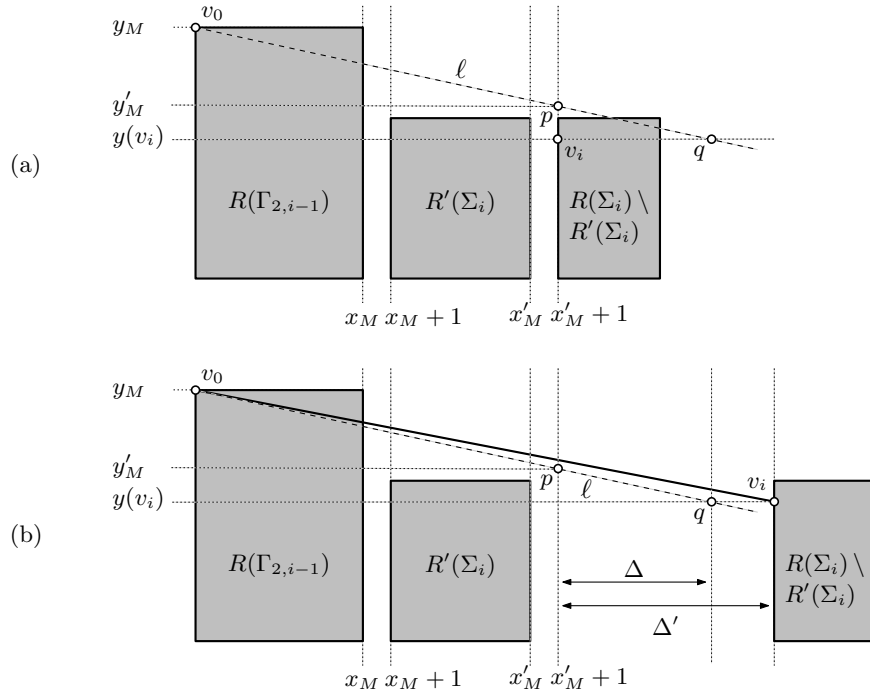


Figure 6: Adding  $\Sigma_i$  to  $\Gamma_{2,i-1}$ .

$\lambda$ . The remainder of the proof focuses on the incremental step that adds  $\Sigma_i$  to  $\Gamma_{2,i-1}$ .

For a drawing  $\Gamma$  we denote by  $R(\Gamma)$  the bounding box of  $\Gamma$ . Let  $(x_M, y_M)$  be the coordinates of the top-right corner of  $R(\Gamma_{2,i-1})$ . Place the drawing  $\Sigma_i$  such that the left side of  $R(\Sigma_i)$  is contained in the vertical line  $x = x_M + 1$ . Let  $R'(\Sigma_i)$  be the (possibly empty) sub-rectangle of  $R(\Sigma_i)$  delimited by the  $x$ -coordinates  $x_M + 1$  and  $x'_M = x(v_i) - 1$ . Furthermore, let  $y'_M$  denote the maximum  $y$ -coordinate of any vertex of  $\Gamma_{2,i-1} \cup \Sigma_i$  distinct from  $v_0$  and let  $p = (x'_M + 1, y'_M)$ ; if  $\Gamma_{2,i-1} \cup \Sigma_i$  does not have any vertex distinct from  $v_0$  we let  $p = (1, y_M - 1)$ . The line  $\ell$  through  $v_0$  and  $p$  crosses neither  $\Gamma_{2,i-1}$  nor the portion of  $\Sigma_i$  contained in  $R'(\Sigma_i)$  (see Figure 6(a)). Let  $q$  denote the intersection of  $\ell$  with the horizontal line at  $y(v_i)$  and let  $\Delta = x(q) - x(v_i)$ . Since  $\Sigma_i$  is  $v_i$ -stretchable, there exists a value  $\Delta' \geq \Delta$  such that we can translate the portion of  $\Sigma_i$  contained in  $R(\Sigma_i) \setminus R'(\Sigma_i)$  to the right by  $\Delta'$  without creating any crossing (see Figure 6(b)). It can easily be verified that the edge between  $v_0$  and  $v_i$  does not have any crossings in the resulting drawing.  $\square$

**Lemma 4** *Let  $G$  be a simple cycle and let  $v$  be any vertex of  $G$ .  $G$  is ULP  $v$ -stretchable.*

**Proof:** Let  $\lambda$  be any  $y$ -assignment of the vertices of  $G$  and let  $u$  be the vertex

of  $G$  that has the smallest  $y$ -coordinate. Let  $u = v_0, v_1, \dots, v_{n-1}$  be the vertices of  $G$  in the order they are encountered when walking clockwise along  $G$ . Place each vertex  $v_i$  at point  $(i, \lambda(v_i))$ . Clearly none of the edges  $(v_i, v_{i+1})$  ( $i = 0, 1, \dots, n-2$ ) cross each other. To avoid crossings between edge  $(v_0, v_{n-1})$  and the other edges we translate  $v_{n-1}$  to the right until the segment connecting  $v_0$  to  $v_{n-1}$  does not cross any other segment. By this construction it follows that such a drawing is  $v$ -stretchable for every vertex  $v$  of  $G$ .  $\square$

**Corollary 6** *Let  $G_1$  and  $G_2$  be two matched graphs such that  $G_1$  is a planar graph and  $G_2$  is a cycle. Then  $G_1$  and  $G_2$  are matched drawable.*

The drawing techniques in [11] imply the following two lemmata.

**Lemma 5** *Let  $G$  be a caterpillar and let  $v$  be a vertex of its spine.  $G$  is ULP  $v$ -stretchable.*

**Lemma 6** *Let  $G$  be a radius-2 star and let  $v$  be the center of  $G$ .  $G$  is ULP  $v$ -stretchable.*

**Corollary 7** *Let  $G_1$  and  $G_2$  be two matched graphs such that  $G_1$  is a planar graph and  $G_2$  is a connected graph consisting of a vertex*

*$v_0$  and a set of disjoint subgraphs  $S_1, S_2, \dots, S_k$ , each  $S_i$  having a single vertex  $v_i$  connected to  $v_0$ . If each  $S_i$  is either a caterpillar with  $v_i$  on its spine, or a radius-2 star with  $v_i$  as its center, or a cycle, then  $G_1$  and  $G_2$  are matched drawable.*

The family of carousel graphs described by Corollary 7 contains graphs that are not ULP. For example, the graph depicted in Figure 3 is a carousel graph with pivot  $v_2$ , and the three seats are caterpillars.

**Remark:** The proof of Theorem 5 is constructive, it can be used to compute a matched drawing for the graphs  $G_1$  and  $G_2$ . However, it may result in a matched drawing that has more than exponential size. For example, let  $G_1$  be a path  $u_0, \dots, u_{n-1}$  and assume that its drawing  $\Gamma_1$  assigns the  $y$ -coordinate  $n-i$  to vertex  $u_i$ . Let  $G_2$  be a star graph with  $v_0$  as its center;  $G_2$  obviously is a carousel graph where each of the  $n-1$  seats is a single vertex (see Figure 7). Let the matching be such that  $u_i$  and  $v_i$  are partners, and let the seats of  $G_2$  be such that  $S_i = v_i$  for  $1 \leq i \leq n-1$ . Suppose that  $v_0 = (0, n)$ , that we have constructed  $\Gamma_{2,i-1}$ , and that  $v_{i-1} = (x_{i-1}, n-i+1)$  for some integer value  $x_{i-1}$ . Then our construction will place  $v_i$  at  $(x_i, n-i)$  with  $x_i > i \cdot x_{i-1}$ , because  $p = (x_{i-1} + 1, n-1)$  and  $q = (i \cdot (x_{i-1} + 1), n-i)$ . It follows that the largest  $x$ -coordinate  $x_{n-1}$  is more than exponential in  $n$ . We do not know whether a polynomial-size matched drawing of a planar graph and a carousel graph which are matched always exists.

### 3.3 Two Trees

Let  $T_1$  and  $T_2$  be two matched trees with  $n$  vertices each. We describe an algorithm to compute a matched drawing of  $T_1$  and  $T_2$  and prove its correctness.

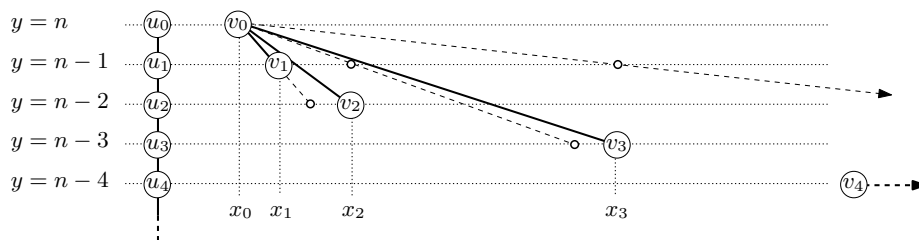


Figure 7: A matched drawing produced by our method that has more than exponential size.

The algorithm has two phases. In the first phase each vertex of a tree  $T_j$  ( $j = 1, 2$ ) is assigned a distinct integer number from 1 to  $n$ , so that two matched vertices receive the same number; we denote by  $\text{ord}(v)$  the number assigned to a vertex  $v$ . Numbers are assigned to vertices in increasing order in  $n$  steps. In the second phase vertices are added to the drawing according to the order defined by the numbers assigned in the first phase.

To describe the two phases we need some definitions. A *chunk of rank  $i$*  is any tree of the forest obtained from  $T_1$  or  $T_2$  by removing all vertices  $v$  that are already processed and have  $\text{ord}(v) \leq i$ . Notice that in Phase 1, a chunk of rank  $i$  is a tree of vertices that have not yet received a number at the end of Step  $i$ ; in Phase 2, a chunk of rank  $i$  is a tree of vertices not yet drawn at the end of Step  $i$ . A chunk  $C$  of rank  $i$  can be adjacent only to vertices  $v$  such that  $\text{ord}(v)$  is defined and  $\text{ord}(v) \leq i$ ; we call these vertices the *anchor vertices of  $C$* . At Step  $i$  ( $1 \leq i \leq n$ ) the *pertinent tree of Step  $i$*  is  $T_1$  if  $i$  is odd and  $T_2$  if  $i$  is even; the other tree is the *non-pertinent tree of Step  $i$* .

### 3.3.1 Description of Phase 1

Phase 1 consists of  $n$  steps. Number  $i$  is assigned to a vertex  $v$  of the pertinent tree of Step  $i$ ; the same number is assigned to the partner of  $v$ . We maintain the following invariant throughout Phase 1:

**Invariant 1** For each integer  $i \in [1, n]$ :

- In the pertinent tree of Step  $i$ , every chunk of rank  $i$  has at most two anchor vertices;
- In the non-pertinent tree of Step  $i$ , there is at most one chunk of rank  $i$  with three anchor vertices, and every other chunk of rank  $i$  has at most two anchor vertices.

At Step 1 the algorithm arbitrarily selects a vertex  $v$  of  $T_1$  and sets  $\text{ord}(v) = 1$ . Assume now that Invariant 1 holds at the end of Step  $i - 1$  ( $i \geq 2$ ). Let  $T_j$  be the pertinent tree of Step  $i$ . Two cases are possible:

**Case 1: In  $T_j$ , every chunk of rank  $(i - 1)$  has at most two anchor vertices.** Let  $C$  be an arbitrary chunk of rank  $(i - 1)$  in  $T_j$ . The algorithm selects any vertex  $v$  of  $C$ , for example one that is adjacent to an anchor vertex of  $C$ , and sets  $\text{ord}(v) = i$  (see Figure 8).

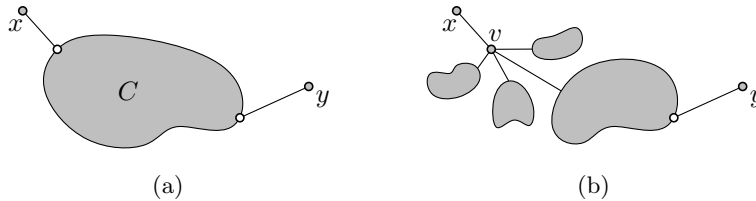


Figure 8: Illustration of Case 1: (a) Chunk  $C$  has two anchor vertices  $x$  and  $y$ . (b) Transformation of  $C$  after  $v$  is selected. In this figure  $v$  is chosen as one of the two vertices adjacent to the anchor vertices of  $C$ .

**Case 2: In  $T_j$ , there exists a chunk  $C$  of rank  $(i - 1)$  with three anchor vertices.** Let  $x, y$ , and  $z$  be the anchor vertices of  $C$ , and let  $\pi_1, \pi_2$ , and  $\pi_3$  the three paths of  $T_j$  from  $x$  to  $y$ , from  $x$  to  $z$ , and from  $y$  to  $z$ , respectively. The algorithm selects the unique vertex  $v$  shared by  $\pi_1, \pi_2$ , and  $\pi_3$ , and sets  $\text{ord}(v) = i$  (see Figure 9).

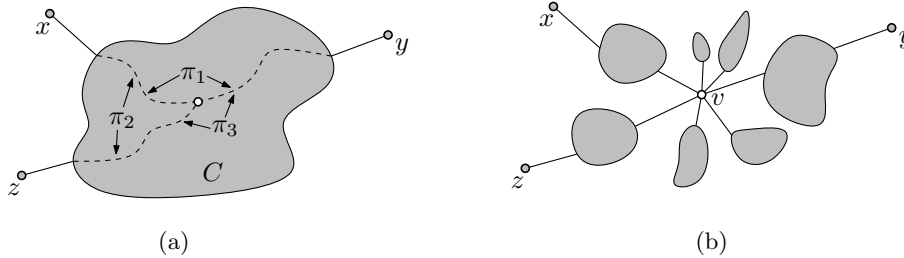


Figure 9: Illustration of Case 2: (a) Chunk  $C$  has three anchor vertices  $x, y$ , and  $z$ . Vertex  $v$  is the unique vertex shared by  $\pi_1, \pi_2$ , and  $\pi_3$ . (b) Transformation of  $C$  after  $v$  is selected.

**Lemma 7** *Invariant 1 holds throughout Phase 1 of the algorithm.*

**Proof:** We prove the lemma by induction. The Invariant holds at Step 1 because all chunks of rank 1 (of both  $T_1$  and  $T_2$ ) are adjacent to the only vertex  $v$  with  $\text{ord}(v) = 1$ . Assume by induction that Invariant 1 holds for  $i - 1$  ( $i \geq 2$ ). Let  $T_j$  be the pertinent tree of Step  $i$  and let  $T_{3-j}$  be the non-pertinent tree of Step  $i$ . Let  $v$  be the vertex of  $T_j$  selected at Step  $i$ .

Assume first that  $v$  was selected according to Case 1. Let  $C$  be the chunk of rank  $i - 1$  that contains  $v$ . In this case, since  $C$  is a tree and since it has at most two anchor vertices,  $C$  is split into at most one chunk with two anchor vertices

(one of which is  $v$  and the other one is an anchor vertex of  $C$ ) and a certain number of chunks with  $v$  as the only anchor vertex (see Figure 8). Assume now that  $v$  was selected according to Case 2. Let  $C$  be the chunk of rank  $i - 1$  that contains  $v$ . Since  $C$  is a tree and since it has three anchor vertices,  $C$  is split into at most three chunks with two anchor vertices (one of which is  $v$  and the other one is an anchor vertex of  $C$ ) and a certain number of chunks with  $v$  as the only anchor vertex (see Figure 9). Therefore Invariant 1 holds for  $T_j$  at Step  $i$ .

Let  $C'$  be the chunk of rank  $i - 1$  in  $T_{3-j}$  that contains the partner  $v'$  of  $v$ . By induction  $C'$  has at most two anchor vertices. Since  $C'$  is a tree, it is split into at most one chunk with three anchor vertices (one of which is  $v'$  and the other two are the anchor vertices of  $C'$ ) and a certain number of chunks with  $v'$  as the only anchor vertex (see Figure 10). Or,  $C'$  is split into at most two chunks with two anchor vertices and a certain number of chunks with  $v'$  as the only anchor vertex. This implies that Invariant 1 also holds for  $T_{3-j}$  at Step  $i$ .  $\square$

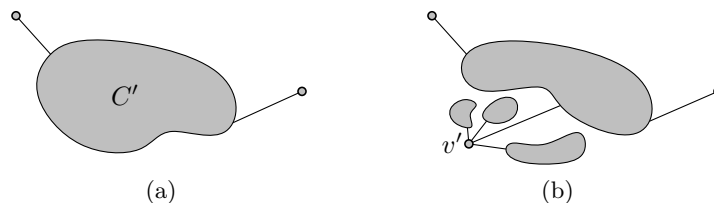


Figure 10: Creation of a chunk with three anchor vertices.

### 3.3.2 Description of Phase 2

Phase 2 also consists of  $n$  steps. At Step  $i$  the algorithm draws the two matched vertices numbered  $i$  in Phase 1. The  $y$ -coordinates are assigned as follows. Let  $v$  and  $v'$  be the two matched vertices with  $\text{ord}(v) = \text{ord}(v') = i$ ; the algorithm sets  $y(v) = y(v') = n - \frac{i-1}{2}$  if  $i$  is odd, and  $y(v) = y(v') = \frac{i}{2}$ , if  $i$  is even. In other words, vertices are assigned consecutively to  $y$ -coordinates  $n, 1, n - 1, 2, \dots$ . Thus, at the end of Step  $i$  there is no vertex drawn yet in the plane strip between the horizontal lines  $y = n - \frac{i-1}{2}$  and  $y = \frac{i-1}{2}$  if  $i$  is odd, and between the horizontal lines  $y = n - \frac{i-2}{2}$  and  $y = \frac{i}{2}$  if  $i$  is even. This strip is called the *strip of rank  $i$*  and it is assumed to be an open set (see Figure 11). The half-plane below the strip of rank  $i$  is called the *bottom side* of the drawing, while the half-plane above the strip of rank  $i$  is called the *top side* of the drawing. In order to assign the  $x$ -coordinates to the vertices, at Step  $i$  each chunk  $C$  of rank  $i$  is associated with a convex polygon  $P$ ;  $C$  will be drawn inside  $P$ . We say that a polygon  $P$  *spans* the strip of rank  $i$  if each horizontal line  $y = j$  with  $j \in \mathbb{N}$  in the strip of rank  $i$  has non-empty intersection with the interior of  $P$ . An edge is drawn when both of its end-vertices are drawn. More precisely, let  $e = (u, v)$  be

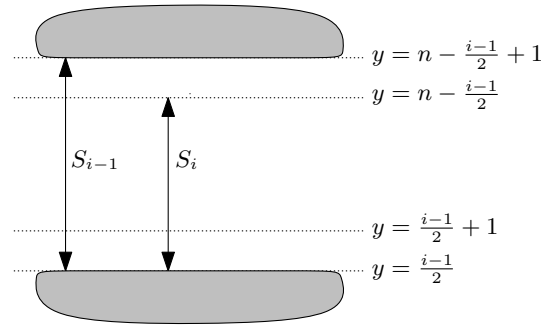


Figure 11:  $S_{i-1}$  is the strip of rank  $i - 1$  and  $S_i$  is the strip of rank  $i$  when  $i$  is assumed to be odd. The top side and bottom side of the drawing at Step  $i - 1$  are the grey parts above and below the strip.

an edge and let  $\text{ord}(u) = j$  and  $\text{ord}(v) = i$  with  $j < i$ . When vertex  $v$  is drawn at Step  $i$ , edge  $e$  is also drawn because  $u$  was drawn before, and we say that  $e$  is an *edge drawn at Step  $i$* . We maintain the following invariant throughout Phase 2:

**Invariant 2** For each integer  $i \in [1, n]$  and for each chunk  $C$  of rank  $i$  in any of the two trees, there exists a convex polygon  $P$  associated with  $C$  such that:

- The anchor vertices of  $C$  are corners of  $P$ ;
- $P$  spans the strip of rank  $i$ ;
- The intersection between  $P$  and any edge  $e$  drawn at some Step  $j$  with  $j \leq i$  is either empty or it consists of an end-vertex of  $e$ ;
- The intersection between  $P$  and the polygon associated with any other chunk of rank  $i$  is either empty or it consists of a common corner;

In what follows we describe how the algorithm assigns  $x$ -coordinates to the vertices of  $T_1$ . The  $x$ -coordinates of the vertices of  $T_2$  are assigned analogously. At Step 1 vertex  $v$  with  $\text{ord}(v) = 1$  is given an arbitrary  $x$ -coordinate. Assume now that Invariant 2 holds at the end of Step  $i - 1$  ( $i \geq 2$ ). Let  $v$  be the vertex with  $\text{ord}(v) = i$ , let  $C$  be the chunk of rank  $i - 1$  that contains  $v$ , and let  $P$  be the polygon associated with  $C$ . We analyze the cases when  $i$  is odd and the cases when  $i$  is even, and their subcases.

**Case 1:  $i$  is odd.** Recall that by Invariant 1, when  $i$  is odd  $C$  can have three anchor vertices. If  $C$  has three anchor vertices, however, they cannot all be on the top side of the drawing. Namely, according to Phase 1, when a chunk with three anchor vertices is created, the next vertex that receives a number is chosen in such a way that the chunk has no longer three anchor vertices. This implies that if a chunk of rank  $i - 1$  has three anchor vertices, one of them is the vertex  $u$  with  $\text{ord}(u) = i - 1$ . Since  $i - 1$  is



even, vertex  $u$  has been drawn at Step  $i - 1$  in the bottom side of the drawing. Therefore at least one anchor vertex is in the bottom side of the drawing. Let  $C_1, C_2, \dots, C_k$  be the chunks of rank  $i$  obtained by splitting  $C$ . Recall that, by Invariant 1 these chunks have at most two anchor points. The position of  $v$  and the polygons  $P_1, P_2, \dots, P_k$  associated with  $C_1, C_2, \dots, C_k$  are computed according to the cases below.

In **Cases 1.1, 1.2,** and **1.3,** at most three chunks among  $C_1, C_2, \dots, C_k$  have two anchor vertices: one of them is  $v$  and the other one is an anchor vertex of  $C$ . All the other chunks have  $v$  as their only anchor vertex. In **Case 1.4** there are at most two chunks among  $C_1, C_2, \dots, C_k$  with two anchor vertices: one of them is  $v$  and the other one is an anchor vertex of  $C$ . All the other chunks have  $v$  as their only anchor vertex.

**Case 1.1:  $C$  has three anchor vertices in the bottom side of the drawing.** In this case vertex  $v$  is assigned an arbitrary  $x$ -coordinate such that the point representing  $v$  is in the interior of  $P$ . The polygons  $P_1, P_2, \dots, P_k$  are computed as shown in Figure 12. More precisely, denote as  $u_1, u_2,$  and  $u_3$  the anchor vertices of  $C$ . Let  $C_1, C_2,$  and  $C_3$  be the chunks having two anchor vertices. Assume that the anchor vertices of  $C_i$  are  $v$  and  $u_i$  ( $1 \leq i \leq 3$ ). Since  $i$  is odd, the strip of rank  $i$  is defined by the two horizontal lines  $y = n - \frac{i-1}{2}$  and  $y = \frac{i-1}{2}$ . Let  $\ell$  be the horizontal line  $y = \frac{i-1}{2} + 1$ , which is contained in the strip of rank  $i$ . Let  $s_i$  be the segment connecting  $v$  to  $u_i$  ( $1 \leq i \leq 3$ ), and let  $p_i$  be the intersection point between  $s_i$  and  $\ell$ . Let  $p_0$  and  $p_{k+1}$  be the intersection points between the border of  $P$  and the horizontal line  $\ell$ . Assume, without loss of generality, that  $p_0, p_1, p_2, p_3,$  and  $p_{k+1}$  appear in this left-to-right order along  $\ell$ . Let  $p_4, p_5, \dots, p_k$  be  $k - 3$  points on  $\ell$  that fall, in this left-to-right order, between  $p_3$  and  $p_{k+1}$ . For each point  $p_i$  ( $1 \leq i \leq k$ ), choose two new points  $p_i^-$  and  $p_i^+$  such that the left-to-right order along  $\ell$  is  $p_0, p_1^-, p_1, p_1^+, p_2^-, p_2, \dots, p_{k-1}^-, p_{k-1}, p_k^-, p_k, p_k^+, p_{k+1}$ . Polygon  $P_i$  associated with  $C_i$  ( $1 \leq i \leq 3$ ) is the polygon whose corners are  $v, p_i^-, p_i^+$ , and  $u_i$ . Let  $q_i$  be the intersection point between the straight line through  $v$  and  $p_i$  and the border of  $P$  ( $4 \leq i \leq k$ ). Polygon  $P_i$  associated with  $C_i$  ( $4 \leq i \leq k$ ) is the polygon whose corners are  $v, p_i^-, p_i^+$ , and  $q_i$ .

**Case 1.2:  $C$  has three anchor vertices, and two of them are in the top side of the drawing.** Let  $\Delta$  be the triangle whose corners are the anchor vertices of  $C$ . Notice that  $\Delta$  is contained in  $P$  and spans the strip of rank  $i$ .

Vertex  $v$  is assigned an arbitrary  $x$ -coordinate such that the point representing  $v$  is in the interior of  $\Delta$ . The polygons  $P_1, P_2, \dots, P_k$  are computed with an approach similar to that of **Case 1.1**. We omit the details and refer to Figure 13(a).

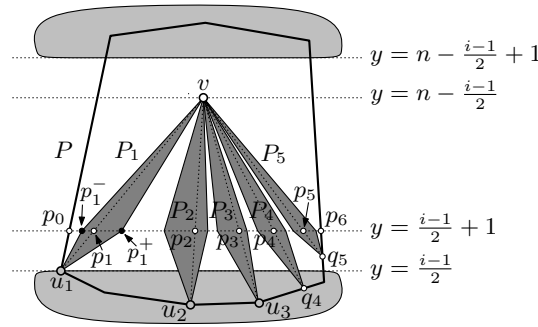


Figure 12: Illustration for **Case 1.1**.

**Case 1.3:**  $C$  has three anchor vertices, and two of them are in the bottom side of the drawing.

The  $x$ -coordinate of  $v$  is computed as in **Case 1.2**. The polygons  $P_1, P_2, \dots, P_k$  are computed as shown in Figure 13(b).

**Case 1.4:**  $C$  has less than three anchor vertices.

This case can be reduced to one of **Cases 1.2**, and **1.3** by selecting one or two corners of  $P$  as dummy anchor vertices. See Figure 13(c) for an example with two anchor vertices.

**Case 2:**  $i$  is even. By Invariant 1, when  $i$  is even  $C$  cannot have three anchor vertices. However, it may happen that at most one of the chunks of rank  $i$  obtained by splitting  $C$  has three anchor vertices. Let  $C_1, C_2, \dots, C_k$  be the chunks of rank  $i$  obtained by splitting  $C$ . The position of  $v$  and the polygons  $P_1, P_2, \dots, P_k$  associated with  $C_1, C_2, \dots, C_k$  are computed according to the following cases:

**Case 2.1:** No chunk of rank  $i$  has three anchor vertices. This case can be handled symmetrically to **Case 1.4**.

**Case 2.2:** A chunk of rank  $i$  has three anchor vertices. In this case  $C$  necessarily has two anchor vertices. Depending on the position of the two anchor vertices of  $C$ , we distinguish between three different cases. In all cases we consider a triangle  $\Delta$  analogous to the one described in **Case 1.2**, i.e. (i)  $\Delta$  is contained in  $P$ ; (ii) all anchor vertices of  $P$  are corners of  $\Delta$ ; (iii)  $\Delta$  spans the strip of rank  $i$ .

**Case 2.2.1:** The two anchor vertices of  $C$  are in the bottom side of the drawing. Vertex  $v$  is assigned an arbitrary  $x$ -coordinate such that the point representing  $v$  is on the border of  $\Delta$ . The polygons  $P_1, P_2, \dots, P_k$  are computed as shown in Figure 13(d).

**Case 2.2.2:** The two anchor vertices of  $C$  are in the top side of the drawing. Vertex  $v$  is assigned an arbitrary  $x$ -coordinate

such that the point representing  $v$  is in the interior of  $\Delta$ . The polygons  $P_1, P_2, \dots, P_k$  are computed as shown in Figure 13(e).

**Case 2.2.3: The two anchor vertices of  $C$  are in different sides of the drawing.** Vertex  $v$  is assigned an arbitrary  $x$ -coordinate such that the point representing  $v$  is in the interior of  $\Delta$ . The polygons  $P_1, P_2, \dots, P_k$  are computed as shown in Figure 13(f).

In all cases above, let  $u$  be an anchor vertex of  $C$ . If  $u$  and  $v$  are not adjacent, then there exists a chunk  $C_j$  of rank  $i$  ( $0 \leq j \leq k$ ), and Figures 12 and 13 show how to compute a polygon  $P_j$  associated with it. If  $u$  and  $v$  are adjacent, then chunk  $C_j$  does not exist, polygon  $P_j$  is not defined and edge  $(u, v)$  is drawn as a straight-line segment. It follows that the intersection between the segment representing  $(u, v)$  and the polygons associated with the chunks of rank  $i$  (or edges connecting  $v$  to other anchor vertices) consists of the single vertex  $v$ . Hence, Invariant 2 is maintained.

**Theorem 8** *Any two trees are matched drawable.*

**Proof:** Let  $T_1$  and  $T_2$  be two matched trees. We prove that the algorithm described above correctly computes a matched drawing of  $T_1$  and  $T_2$ . By Lemma 7, Phase 1 computes an order of the vertices that satisfies Invariant 1. Phase 2 uses this order to draw the vertices.

First of all, notice that in each of the cases considered in the description of Phase 2, a point to represent  $v$  exists. Namely, in all cases  $v$  has a  $y$ -coordinate that is assigned depending only on the value of  $i$ : it is either  $y = n - \frac{i-1}{2}$ , or  $y = \frac{i}{2}$ . So in each case  $v$  must be drawn on a point of a horizontal line  $\ell$  that is either  $y = n - \frac{i-1}{2}$ , or  $y = \frac{i}{2}$ . In **Case 1.1** the algorithm chooses a point of  $\ell$  that is inside  $P$ . Since  $P$  spans the strip of rank  $i$ , the intersection between the interior of  $P$  and  $\ell$  is not empty. In all other cases the algorithm chooses a point that is either in the interior of triangle  $\Delta$ , or on its border. Since the number of anchor points of  $C$  is at most three, and since if there are three anchor vertices then they are on different sides (because otherwise we are in **Case 1.1**), a triangle  $\Delta$  exists with three corners  $a$ ,  $b$ , and  $c$  such that: (i)  $a$ ,  $b$ , and  $c$  are corners of  $P$ ; (ii) all anchor vertices of  $C$  are in the set  $\{a, b, c\}$ ; (iii)  $a$ ,  $b$ , and  $c$  are not all on the same side of the drawing. By construction,  $\Delta$  is contained in  $P$  and all anchor vertices of  $C$  are corners of  $\Delta$ . Also,  $\Delta$  spans the strip of rank  $i$  because it has at least one corner in the bottom side of the drawing and at least one corner in the top side of the drawing. Since  $\Delta$  spans the strip of rank  $i$ , at least one point of  $\ell$  inside  $P$  exists that can be used to represent  $v$ .

Invariant 2 holds throughout Phase 2 by construction. It remains to prove that the drawings computed by the algorithm form a matched drawing of  $T_1$  and  $T_2$ . Since two matched vertices have the same  $y$ -coordinate, we only need to show that the drawings of  $T_1$  and  $T_2$  are planar. We prove this for  $T_1$ ; an analogous proof holds for  $T_2$ .

Consider two edges  $e_1$  and  $e_2$  in the drawing of  $T_1$ . Assume that  $e_1$  is an edge drawn at Step  $j$ , and that  $e_2$  is an edge drawn at Step  $i$ , with  $j \leq i$ . If

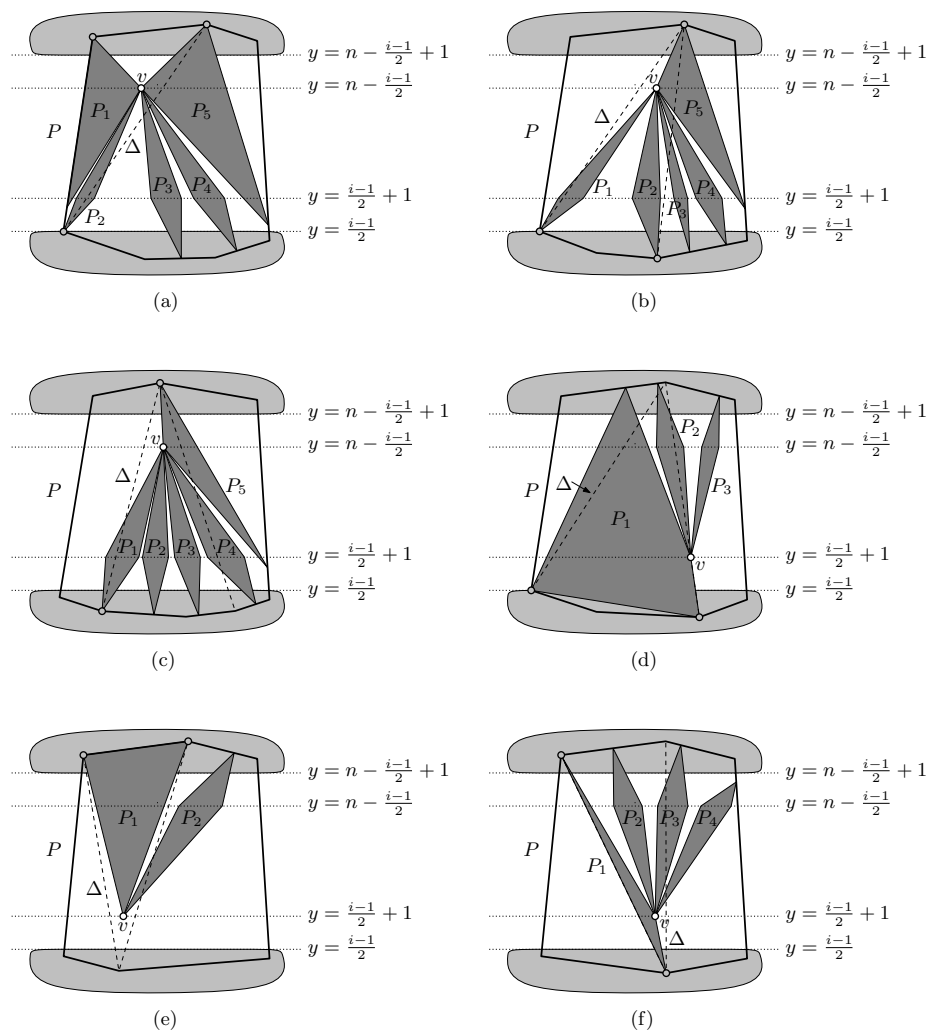


Figure 13: (a) Case 1.2; (b) Case 1.3; (c) Case 1.4; (d) Case 2.2.1; (e) Case 2.2.2; (f) Case 2.2.3.

$j = i$  then  $e_1$  and  $e_2$  share an endvertex (the one drawn at Step  $i$ ) and they cannot cross. If  $j < i$ , edge  $e_1$  is drawn before edge  $e_2$ . Let  $v$  be the endvertex of  $e_2$  that is drawn at Step  $i$ , let  $C$  be the chunk of rank  $i - 1$  that contains  $v$ , and let  $P$  be the polygon associated with  $C$ . Edge  $e_2$  is drawn inside  $P$ , since  $e_2$  connects  $v$  to an anchor vertex of  $C$ , which is a corner of  $P$ . By Invariant 2, the intersection between  $P$  and  $e_1$  is either empty or it consists of an endvertex of  $e_1$ . Thus  $e_1$  and  $e_2$  either have no intersection or they share a common endvertex.  $\square$

## 4 Conclusions and Open Problems

In this paper we introduced the concept of matched drawings, which are a natural way to draw two planar graphs whose vertex sets are matched. Since this is the first study of these drawings, many interesting and challenging open problems remain. First of all, in the light of Theorems 2 and 5, we would like to characterize the subclass of planar graphs that admit a matched drawing with any planar graph. Secondly, the drawing techniques of Theorems 5 and 8 may give rise to drawings where the area is at least exponential in the size of the graphs. It would be interesting to determine for what classes of graphs polynomial-size matched drawings exist. On a related note, some of our drawing techniques rely on a planar straight-line drawing of a planar graph where each vertex has a different  $y$ -coordinate. How big a grid is necessary to guarantee such a drawing with integer coordinates? Another question concerns the counterexample for a planar graph and a tree described in Section 2.2, which consists of 620 vertices. It would be nice to construct a counterexample with a smaller number of vertices. And finally, given any two matched graphs, what is the algorithmic complexity of testing whether they are matched drawable?

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