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Towards a Topology-Shape-Metrics Framework for Ortho-Radial Drawings

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Abstract

Ortho-Radial drawings are a generalization of orthogonal drawings to grids that are formed by concentric circles and straight-line spokes from the center.

We show that bend-free planar ortho-radial drawings can be combinatorially described in terms of the distribution of the angles around the vertices. Previously, such a characterization was only known for paths, cycles, and theta graphs [5], and in the special case of rectangular drawings for cubic graphs [4], where the contour of each face is required to be a rectangle. This is an important ingredient in establishing an ortho-radial analogue of Tamassia’s Topology-Shape-Metrics Framework for bend minimization in planar orthogonal drawings.

1 Introduction

Grid drawings of graphs map vertices to grid points, and edges to internally disjoint curves on the grid lines connecting their endpoints. Orthogonal grids, where the grid lines are horizontal and vertical lines, are popular and widely used in graph drawing. Their strength lies in their simple structure, their high angular resolution, and the limited number of directions. Graphs admitting orthogonal grid drawings must be 4-planar, i.e., they must be planar and have maximum degree 4.

It is well known that, a bend-free planar orthogonal drawing \( G \) of a 4-plane graph \( G \), i.e., a 4-planar graph with a fixed combinatorial embedding, can be combinatorially described by the distribution of the angles around the vertices. For any incidence between a vertex \( v \) and a face \( f \) that lies to the right of the edges \( uv, vw \), we measure the counterclockwise angle \( \alpha \in \{90°, 180°, 270°, 360°\} \) between \( uv \) and \( vw \). In this way, we assign an angle to each vertex–face incidence. Consider two edges \( uv, vw \) not necessarily bounding a common face and let \( \alpha \) be the sum of all the angles that lie locally to the right of \( uv \). We define the rotation of the path \( uvvw \) as \( \text{rot}(uvw) = 2 - \alpha/90° \), i.e., intuitively left and right turns correspond to rotations of \(-1\) and \(1\), respectively, whereas going straight corresponds to a rotation of \(0\). We further generalize this to arbitrary paths \( P = v_1, \ldots, v_k \) as \( \text{rot}(P) = \sum_{i=2}^{k-1} \text{rot}(v_{i-1}v_iv_{i+1}) \) and to cycles \( C = v_1, \ldots, v_k, v_1 \) as \( \text{rot}(C) = \sum_{i=1}^{k} \text{rot}(v_{i-1}v_iv_{i+1}) \), where \( v_0 = v_k \) and \( v_{k+1} = v_1 \). For a face \( f \), we define \( \text{rot}(f) = \text{rot}(C_f) \) where \( C_f \) is the boundary of \( f \) directed such that \( f \) lies to its right. It is not hard to see that an angle assignment stemming from an orthogonal drawing satisfies the following conditions.

1. The sum of the angles around each vertex is 360°.
2. For each internal face \( f \) it is \( \text{rot}(f) = 4 \) and \( \text{rot}(f) = -4 \) for the outer face.

An angle assignment satisfying these conditions is called orthogonal representation. Tamassia [6] showed that, conversely, for any orthogonal representation there exists a corresponding planar orthogonal drawing with the given angles. It is this characterization, which decouples the shape of an orthogonal drawing (described in the form of an orthogonal representation) from its geometric realization, that has enabled a three-step framework for computing orthogonal planar drawings, the Topology-Shape-Metrics (TSM) framework, that is at the heart of various bend minimization algorithms for orthogonal drawings [6, 1, 2, 3]. Note that bends can be seen as subdivision vertices with a 90° and a 270° angle.

The goal of this work is to provide a similar result and thus to establish the existence of an analogous framework for ortho-radial drawings, which are based on ortho-radial grids formed by concentric circles and spokes emanating from the circles’ center \( c \); see Fig. 1a. In this case, our 4-plane input graph \( G \) comes with two designated faces, an outer face, which shall form the outer face of the drawing and a central face whose interior shall contain \( c \). All other faces are regular. A simple cycle in \( G \) is essential if it contains \( c \) in its interior, otherwise it is non-essential. Throughout this paper we assume that \( G \) contains at least one
essential cycle. If it does not, then the central and the outer face are identical, and the ortho-radial drawing is equivalent to an orthogonal drawing [5].

It is not hard to see that also ortho-radial drawings induce angle assignments as above, which we call **ortho-radial representations**. It is clear that again the angle sums around each vertex must be 360°, and further similar to the orthogonal case, it is \( \text{rot}(f) = 4 \) for regular faces and \( \text{rot}(f) = 0 \) for the central and the outer face (recall that we assume them to be distinct). However, there are examples of such assignments that have no geometric realization; see Fig. 1b. Up to this point a characterization of the ortho-radial representations that have a corresponding drawing has been achieved only for paths, cycles, and theta-graphs [5].

However, there are examples of such assignments that are not monotone. For an essential cycle \( C \) with a given ortho-radial representation \( \Gamma \), we fix an arbitrary reference edge \( e^* = rs \) on the outer face that points to the right, i.e., the outer face lies on its left. Let \( C \) be a simple essential cycle and let \( P \) be a path from \( s \) to a vertex \( v \) of \( C \). We now define a labeling of the edges of \( C \) with respect to \( P \) and \( e^* \) as \( l_C^P(e) = \text{rot}(e^* + P + C[v,e]) \), where \( C[v,e] \) denotes the part of \( C \) from \( v \) to \( e \). In the following we are mostly interested in labelings with respect to so-called **elementary paths** \( P \), where \( v \) is the first vertex of \( C \) that lies on \( P \). It can be shown that in this case the labeling does not depend on the choice of the elementary path. Thus, the labeling of \( C \) depends only on \( \Gamma \), and we omit the superscript \( P \). We are now ready to present our characterization.

**Definition 1** An **ortho-radial representation** is valid if the following conditions hold.
1. The sum of angles around each vertex is 360°.
2. For each face \( f \), it is
   \[ \text{rot}(f) = \begin{cases} 4, & \text{if } f \text{ is a regular face} \\ 0, & \text{if } f \text{ is the central/outer face.} \end{cases} \]
3. For each simple essential cycle \( C \) in \( G \), it is
   \[ l_C^P(e) = 0 \]
   for all edges \( e \) of \( C \), or there are edges \( e_+ \) and \( e_- \) on \( C \) with \( l_C^P(e_+) > 0 \) and \( l_C^P(e_-) < 0 \).

We have already seen that the first two conditions are necessary. The last condition is new and guarantees that all cycles in the graph can be drawn consistently. For an essential cycle \( C \) that violates condition 3 either all labels of edges on \( C \) are non-negative or all are non-positive. Then \( C \) is called **decreasing** and **increasing**, respectively. Both increasing and decreasing cycles are called **monotone**. Note that an increasing (decreasing) cycle contains an edge with a negative (positive) label. Cycles with only the label 0 are not monotone. Our main result is as follows.

**Theorem 1** Let \( G \) be a 4-plane graph with an ortho-radial representation \( \Gamma \). Then \( G \) has an ortho-radial drawing that corresponds to \( \Gamma \) if and only if \( \Gamma \) is valid.

## 3 Rectangular Graphs

Let \( G \) be a 4-planar graph and let \( \Gamma \) be an ortho-radial representation of \( G \) where every face is rectangular. We use a flow method similar to Tamassia [6]. For each edge \( e \), we find an arbitrary path \( P \) from \( e^* \) to \( e \), and we determine \( e \) as pointing right, down, left or up, if \( \text{rot}(P) \mod 4 = 0, 1, 2, \text{ or } 3 \), respectively. We note that conditions 1 and 2 of valid ortho-radial representations guarantee that this is well-defined. We then reverse the downward and left edges so that all edges point either up or right. The rectangular property of the faces guarantees that each internal face is bounded by two vertical and by two horizontal paths.
We create a radial flow network $N_{rad}$ with a vertex for each face, and an edge from a face $f$ to a face $g$ if and only if there is a horizontal edge with $f$ to its right and $g$ to its left; see Fig. 2. Similarly, we define a vertical flow network $N_{ver}$ that has a vertex for each internal face and an edge from $f$ to $g$ if and only if there is a vertical edge with $f$ to its left and $g$ to its right. We set the capacities of all edges to $\infty$ and require a minimum flow of 1 on each edge. It is then readily seen that drawings of $\Gamma$ correspond bijectively to pairs $(F_{rad}, F_{ver})$ where $F_{rad}$ is a flow from the central face to the outer face in $N_{rad}$ and $F_{ver}$ is a circulation in $N_{ver}$. The fact that such a flow exists in $N_{rad}$ is analogous to the orthogonal case [6].

The key is to show that a circulation in $N_{ver}$ exists if $\Gamma$ is valid. The main idea is to determine for each arc $a$ of $N_{ver}$ a cycle $C_a$ in $N_{ver}$ that contains $a$. If $F_a$ denotes the circulation that pushes one unit of flow along the arcs of $C_a$ and is 0 elsewhere, then $F_{ver} = \sum_{a \in A} F_a$, where $A$ denotes the arc set of $N_{ver}$, is the desired flow. The only reason why such a cycle might not exist is if there is a set $S$ of vertices in $N_{ver}$ such that there exists an arc entering $S$ but no arc exiting $S$. Without loss of generality, we assume $N_{ver}[S]$ is weakly connected, which implies that $S$ corresponds to a connected set $S$ of faces in $G$. Note that $S$ contains a directed cycle of $N_{ver}$, which is an essential cycle. Let $C$ and $C'$ denote the smallest and largest essential cycle of $G$, respectively, such that all faces in $S$ lie in the interior of $C$ and in the exterior of $C'$. We show that $C$ is increasing or $C'$ is decreasing.

Assume there is an incoming arc $a$ that crosses $C$ (an incoming arc crossing $C'$ is analogous). Since all faces are rectangles, there is an elementary path $P$ from $e^*$ to a vertex $v$ on $G$ only using right and down edges of $G$. Thus, if $w$ is the first vertex of $C$ after $v$, it is $\ell_C(w) = 0$ if $vw$ is horizontal and $\ell_C(vw) = -1$ if $vw$ points up. Since no edge on $C$ is pointing downward, i.e., its label is congruent to 1 mod 4, and the labels between adjacent edges differ by $-1, 0$, or 1, it follows that $\ell_C(e') \in \{-2, -1, 0\}$ for all edges $e'$ of $C$, i.e., $\ell_C(e') \leq 0$. However, the edge $e$ corresponding to the incoming arc $a$ of $S$ is pointing upwards, and therefore $\ell_C(e) = -1$. Hence $C$ is increasing.

**Theorem 2** Let $(G, \Gamma)$ be a rectangular graph and its ortho-radial representation. There exists a bend-free ortho-radial drawing of $G$ respecting $\Gamma$ if and only if $\Gamma$ is valid.

4 General 4-planar Graphs

In this section we present the proof of Theorem 1. Following Tamassia’s approach for orthogonal drawings [6], our approach is based on augmenting a graph $G$ and its valid ortho-radial representation with additional edges so that it remains valid and becomes rect-
process of subdividing $e_i$ with a new vertex $z$ and adding the edge $uz$ augmenting with $e_i$. Intuitively, augmenting with $e_i$ makes a jump further downwards as $i$ increases. Indeed, using similar arguments as the ones for the vertical case, one can show that the first candidate never creates an increasing cycle, and the last candidate never creates a decreasing cycle.

**Lemma 4** Augmenting with $e_1$ (resp. with $e_k$) never creates an increasing (resp. decreasing) cycle.

Moreover, it can be shown that an increasing and a decreasing cycle cannot intersect strictly, and therefore, it is not possible that augmenting with a candidate creates both an increasing and a decreasing cycle. Thus, if each augmentation with respect to the edges $e_i$ yields an increasing or a decreasing cycle, then by Lemma 4, there exists a pair of candidates such that $e_i$ creates a decreasing cycle and $e_{i+1}$ creates an increasing cycle. Let $e_i = vw$ and $e_{i+1} = v'u'$ be directed so that $f$ lies to their right and note that possibly $v' = w$. Let $z$ and $z'$ denote subdivision vertices of $e_i$ and $e_{i+1}$, respectively. We simulate augmentation with both candidates simultaneously by inserting two vertices $x$ and $y$ as shown in Fig. 3c. By construction, we then find both a decreasing cycle $C$ using the edges $ux, xz$ and a cycle $C'$ using the edges $ux, xy, yz'$ that is increasing except for possibly the edge $xy$. Since these cycles both contain $u$ but one is decreasing and the other one is increasing, and such cycles cannot strictly intersect, we can infer that, outside of the face $f$ both cycles actually coincide, i.e., their edges all have label 0 outside of $f$. We thus find a path $P$ in $G$ consisting of only horizontal edges that starts at $v'$ or at $w$, ends at $u$ and contains all these vertices. Thus, augmenting the graph $G$ by adding the edge from $u$ to the starting point of $P$ creates a cycle consisting of only horizontal edges. It can be argued that such an augmentation is always safe. In fact one can show that no monotone cycle can share a vertex with a horizontal cycle. The following lemma summarizes this discussion.

**Lemma 5** Let $f$ be a face and let $u$ be a vertex on the boundary of $f$ that forms a left bend in $f$. Let further $e = vw$ and $e' = v'u'$ be two consecutive candidates. If augmentation with $e$ creates an increasing cycle and augmentation with $e'$ creates a decreasing cycle, then augmenting with one of $uw$ or $uv'$ does not create a monotone cycle.

Altogether, this proves that for each left bend in a regular face $f$ there exists an augmentation such that the resulting graph and ortho-radial representation are still valid. Eventually, we thus arrive at a rectangular graph, and Theorem 2 applies.

5 Conclusion

In this work we considered orthogonal drawings of graphs on cylinders. Our main result is a characterization of the 4-plane graphs that can be drawn bend-free on a cylinder in terms of an ortho-radial representation of such drawings.

While our proof for both the rectangular case and the general case are algorithmic, only the former currently has an efficient implementation, e.g., in terms of a flow algorithm. In contrast, the rectangulation procedure from Section 4 requires checking whether augmentations create monotone cycles. Our most important open problem is whether such a check can be performed in polynomial time.

**References**


