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**On Maximizing The Euclidian Distance Between Vertices  
In Small Area Drawings Of Maximal Series Parallel  
Graphs**

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## Abstrakt

Graphenzeichnungen sind vielfach anwendbar - für die Analyse der Molekularstrukturen oder Sensornetzen sind Zeichnungen mit vorbestimmten Distanzen von besonderer Bedeutung. Das *Graph Drawing Symposium* fordert im Jahre 2022 die Teilnehmer des dort stattfindenden Wettbewerbs auf, Zeichnungen auf kleiner Fläche anzufertigen und dabei die Distanzen der paarweise verbundenen Knoten zu maximieren. In *geradlinigen Zeichnungen* werden Knoten mit einem einzigen Liniensegment verbunden. Um die jeweiligen Distanzen zwischen Knoten zu maximieren, ist eine Umpositionierung der Knoten erforderlich. Dies erweist sich bei geradlinigen Zeichnungen als bedingt möglich. Lässt man *Polygonzüge* zu, erweitert dies die Möglichkeiten der Knotenrepositionierung. Bei einer *Polygonzugzeichnung* wird eine Verbindung zwischen zwei Knoten als eine Sequenz von Liniensegmenten mit unterschiedlicher Steigung, welche sich in einem Punkt schneiden, dargestellt. Dieser Schnittpunkt wird im Allgemeinen *Knick* genannt. Die Optimierungsfunktion wird als das Verhältnis zwischen der kürzesten euklidischen Distanz zwischen zwei verbundenen Knoten und dem gesamten Flächenverbrauch beschrieben. Dieses Verhältnis wird die *Ratio* genannt.

Anlässlich der diesjährigen Symposium Challenge untersucht dieses Ausarbeitung die Maximierung der euklidischen Distanz für die Klasse der *verwurzelten Bäume* und der *maximalen seriell-parallelen Graphen*. Im Allgemeinen ist die Klasse der Bäume durch ihre überschaubaren Eigenschaften eine gute erste Anlaufstelle zur Untersuchung eines Optimierungsproblems. Da die Klasse der maximal seriell-parallelen Graphen um einiges vielseitiger in ihren Eigenschaften ist, ist die Optimierung von dessen Zeichnungen mit geringem Platzverbrauch von hohem Interesse.

Zuerst wird ein Zeichenalgorithmus für verwurzelte Bäume präsentiert, welcher geradlinige Zeichnungen mit einer optimalen Ratio erstellt.

Darauffolgend wird eine Subklasse der maximal seriell-parallelen Graphen, die sogenannten *maximal outerplanaren Graphen* untersucht. Es wird gezeigt, dass die Ratio *unbeschränkt* ist, was heißt, dass es für jeden maximal outerplanaren Graphen einen größeren gibt, der das Ratio der dementsprechenden Zeichnung signifikant erhöht.

Ein erster Ansatz für eine Polygonzugzeichnung setzt sich mit maximal outerplanaren Graphen hoher Dichte auseinander. Die Begrenzungen dieses Ansatzes dienen zur Inspiration für einen zweiten, allgemeineren Ansatz. Dieser zweite Ansatz dient als eine Grundlage für die Erstellung von Polygonzugzeichnungen von maximal seriell-parallelen Graphen. Die Ansatzweiterung resultiert in einem Zeichenalgorithmus, welcher Polygonzugzeichnungen von maximalen seriell-parallelen Graphen auf vertretbar kleiner Fläche produziert, sodass die Ratio in einem angemessenen Rahmen bleibt.

Zusätzlich wurde eben dieser Ansatz auf eine restriktivere Klasse an Graphen, den sogenannten *3-Trees*, angewandt. Es wird illustriert, dass dieser Ansatz bezüglich der Ratiooptimierung für die Klasse der 3-Trees unzureichend ist.

## Abstract

Graph drawings are diverse in their applications - regarding molecular structure analysis or sensor networks, constructing a drawing with certain properties of distance is of interest. In the year 2022, the *Graph Drawing Symposium* challenges its participants to create small area drawing with maximizing the distances between two adjacent vertices. In a *straight-line drawing*, adjacent vertices are connected by a single line segment. In order to increase the distance between vertices, the vertices are repositioned in a fixed area. In straight-line drawings, the repositioning might be limited in its possibilities. Allowing *poly-lines* loosens this limitation. In a *polyline drawing*, every edge is illustrated as a sequence of line segments which intersect in a point, so-called *bends*. The optimization problem is described as the proportion between the length of the Euclidian distance to the total area consumption. This will be called the *ratio* of a drawing.

On occasion of this Symposium challenge, this thesis will examine the maximization of the *Euclidian distance* on *rooted trees* and small area drawings of the class of *maximal series-parallel graphs*. For a given drawing problem, the class of trees are rather manageable due to their straightforward properties. The graph class of maximal series-parallel graphs is more complex in its properties than rooted trees and investigating the distance maximization of those small area drawings is of particular interest.

First, a drawing algorithm for rooted trees is presented which produces straight-line drawings with uniform distances between adjacent vertices.

Next, the *maximal outerplanar graphs*, a subclass of maximal series-parallel graphs, are investigated for Euclidian distance maximization on small area polyline drawings. It will be proved that they are unbounded, meaning that for every maximal outerplanar graph there exists a larger graph which exceeds the ratio in the respective drawing.

A first approach of a polyline drawing algorithm deals with maximal outerplanar graphs of high density. Its limitations will inspire a new idea for dealing with more general occasions. Then, a second approach will serve as a foundation to be extended for the class of maximal series-parallel graphs. An extension of this approach will produce small area polyline drawings for maximal series-parallel graphs with a reasonable ratio.

In the extensional work, the previous approaches and results will be applied to a more restrictive class of graphs, called the *3-trees*. It will be demonstrated that the approach for maximal series-parallel graphs is not applicable to the class of 3-trees regarding ratio optimization.

## Erklärung

Hiermit erkläre ich, dass ich diese schriftliche Abschlussarbeit selbstständig verfasst habe, keine anderen als die angegebenen Hilfsmittel und Quellen benutzt habe und alle wörtlich oder sinngemäß aus anderen Werken übernommenen Aussagen als solche gekennzeichnet habe.

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Datum, Ort, Unterschrift

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# 1 Introduction

The topic of visualization of information relationships occur in various areas of work. Examples of the fields include circuit design, architecture, web science, social sciences, biology, geography, information security and software engineering. Over the last decades, many different efficient algorithms were developed for graph drawings in the Euclidean plane. Different quality measures for graph drawings have been considered, including area consumption, angular resolution, slope number, average edge length, and total edge length, addressing the readability and aesthetics [6].

Graphs admitting a *crossing-free* drawing are called *planar* graphs and have a long history in graph theory. This well-developed theory can be used to simplify topological concepts that otherwise would prove cumbersome [3, P. 9]. In

context of this thesis, drawings with prescribed edge lengths is of particular interest. Its relevance addresses aspects of computational geometry, rigidity theory, structural analysis of molecules and sensor networks [1, P. 1]. In general, it is hard to decide [1, P. 2] whether a given graph admits a drawing with prescribed edge lengths under the condition that any edge is drawn with a straight-line and no two edges cross each other, even in the case of uniform lengths for all edges.

Starting from a workshop in 1994, the first international conference for *Graph Drawing* was held in Passau in 1995 [16]. The annual symposium covers topics of combinatorial and algorithmic aspects of graph drawing as well as the design of network visualization systems and interfaces.

One part of the symposium is the *Graph Drawing Contest*. The contest consists of two parts - the *Creative Topics* and the *Live Challenge*. The main focus for the Creative Topics lies on the creation of drawings of two given graphs. Aspects to consider for the visualization are clarity, aesthetic appeal and readability.

On the other hand, the Live Challenge is held similar to a programming contest. Participants, usually teams, will get a task and will have one hour of processing a set of exemplary graphs. The results will be ranked and the team with highest score wins the competition. The teams will be allowed to use any combination of software and human interaction systems in order to produce the best results. Usually, the challenge is derived from a theoretical optimization problem [10].

In 2021, the Live Challenge during the 29th International Symposium on Graph Drawing and Network Visualization held in Tübingen, Germany addressed the optimization of graph drawing edge lengths. An *edge length ratio* of a drawing describes the proportion between the *minimal and maximal edge lengths*. The size of the total area of a drawing affects the maximum edge length. When considering *straight-line drawings*, where edges are a single straight line segment, the ratio scales in proportion of the total area size. For the *Live Challenge*, the goal was to produce a *polyline graph drawing*, where edges are line segments joined together, with uniform edge lengths. The difficulty of this challenge was intensified by constraints on the drawing area and the amount of line segments per edge [11].



In 2022, the 30th International Symposium of Graph Drawing and Network Visualization held in Tokyo, Japan [12] addresses an alternation of the Live Challenge from previous year. In contrast to the edge length ratio from 2021, this years ratio describes the proportion of the *maximal polyline edge length* to the *minimal Euclidian distance* between two adjacent vertices.

This thesis will address the topic of minimizing the difference between the longest and shortest edge length for certain graph classes. The main goal is to maximize the distances between two adjacent vertices while keeping the area consumption of the resulting drawing at a low level. Allowing to reroute edges through so-called *bend points* in a drawing without causing crossings between edges increases the flexibility of finding an approach for the edge length difference minimization approach.

In Section 2, the preliminaries and terminology are defined. In Section 3, the general problem considering the edge length ratio is formalized. Furthermore, the potential for ratio improvement is illustrated by allowing polyline edges. Section 4 describes a drawing algorithm for the graph class of *k-ary trees* which guarantees a satisfying edge length ratio. Section 5 examines the properties of *maximal outerplanar* graphs, a subclass of *maximal SP-graphs*, and demonstrates two drawing algorithms. Section 6 contains an extension of a drawing algorithm for maximal outerplanar graphs in order to draw a *maximal series-parallel graphs* with a reasonable ratio. Section 7 addresses the applicability of the main approach for other classes of planar graphs. It will be demonstrated that the approach for maximal series-parallel graphs does not suffice for a more restricted class of planar graphs, the planar *3-trees*.

## 2 Preliminaries

### 2.1 Definitions And Terminology

A *graph*  $G = (V, E)$  is a tuple consisting of two sets - the set of vertices  $V = V(G)$  and the set of edges  $E = E(G)$ . An *edge*  $e = (v, w), v, w \in V$  is a tuple and describes a connectivity relation between two vertices. If  $V' \subseteq V, E' \subseteq E$ , then  $G' = (V', E')$  is a *subgraph* of  $G$ . The *degree* of a vertex states the amount of edges incident to the vertex.

A *path* of length  $k$  from a vertex  $v_1$  to  $v_{k+1}$  is a sequence of vertices  $(v_1, \dots, v_{k+1})$  such that  $(v_i, v_{i+1})$  is an edge in  $G$ . A path is *simple* if all the vertices in the sequence are distinct. A *cycle* is a path where  $v_1 = v_{k+1}$  and has at least one edge. A graph with no cycles is called *acyclic* [7, P. 1170].

Unless otherwise mentioned, the graphs are *undirected*, meaning that the edge  $(u, v)$  is identical to the edge  $(v, u)$ . An undirected graph is *connected* if every vertex is reachable from all the other vertices [7, P. 1170]. A graph is *biconnected* if the removal of any vertex still leaves the graph connected [9, P. 224]. A graph is *simple* if it does not contain neither multiple edges nor self loops. On the other hand, if a graph contains multiple edges or self loops, it is called a *multigraph* [7, P. 1172]. Unless otherwise mentioned, a graph is presumed to be simple.

The *depth-first search*, *DFS* in short, is a strategy to explore edges out of the most recently discovered vertex  $v$  that still has unexplored edges leaving it. Once all of  $v$ 's edges have been explored, the DFS backtracks in order to explore edges leaving the vertex from which  $v$  was discovered. The DFS terminates when all the reachable vertices from the original source vertex were discovered [7, P.603].

### 2.2 Graph Drawing Models And Representations

An  $h \times w$  *grid* is a graph consisting of  $h$  rows and  $w$  columns of vertices. The vertex in the  $i$ -th row and  $j$ -th column is denoted as  $(i, j)$  and is called a *grid point*. All vertices in a grid have exactly four neighbours, except for the boundary vertices [7, P. 760]. One *unit length* values the distance between two adjacent vertices on the grid and is denoted as  $UL$ . A *drawing*  $\Gamma$  of a graph  $G$  is a function, where each vertex is mapped on a unique point  $\Gamma(v)$  in the plane and each edge is mapped on an open Jordan curve  $\Gamma(e)$  ending in its vertices [9, P. 225]. In this context, a graph will be drawn on an underlying grid.

A drawing is called *planar* if no two distinct edges intersect. A graph is *planar* if it admits a planar drawing [7, Page 100]. A drawing partitions the plane into topologically connected regions [3, P. 7]. A *face* is a maximal open region of the plane bounded by edges. The *outer face* is the unbounded face. A bounded face is called *inner face* [8, S. 86].

A multigraph  $G^*$  is the *dual graph* of  $G$  if and only if there exists a bijective function between  $G^*$  and  $G$  such that:

1. Every face  $f$  in  $G$  corresponds to a vertex  $v_f$  in  $G^*$
2. For every edge  $e$  of  $G$ , the corresponding vertices of the faces in  $G^*$  incident to  $e$  get an edge

3. If  $e$  is incident to only one face, a loop is attached to the corresponding vertex in  $G^*$

[8, P. 103] The *weak dual graph* of  $G$  is the dual graph of  $G$  without considering the outer face.

An *embedding* of  $G$  is the collection of counter-clockwise circular orderings of edges around each vertex of  $V$ , denoted as a sequence of edges.

In a *straight-line drawing*, vertices are points on the grid and edges are straight-line segments.

In a *polyline drawing*, vertices are points on the grid, edges are sequences of contiguous straight-line segments. The transition point between two edge segments with different slopes is called a *bend*. Like vertices, bends are placed on points on the underlying grid.

A *box* is an axis-parallel rectangle, overlapping vertical and horizontal grid lines. The *width* of a box is one unit smaller than the number of vertical grid lines that are overlapped by it. The *height* of a box is one unit smaller than the number of horizontal grid lines that are overlapped by it. In an *orthogonal box drawing*, vertices are axis-aligned boxes (possibly degenerated to a line segment or a point), edges are sequences of contiguous horizontal or vertical line segments. [5, P. 144ff]

A *layering* is a mapping  $L : V \rightarrow \mathbb{N}$  and determines the horizontal grid line placement of a vertex. A layering is *valid*, if  $|L(u) - L(v)| \geq 1$  for any edge  $(u, v)$  [15, P. 4].

A drawing whose minimum enclosing box has width  $w$  and height  $h$  is called a  $w \times h$ -drawing and inherits area  $w \cdot h$  [5, P. 145].

The *euclidian distance* between two grid points  $(x_1, y_1)$  and  $(x_2, y_2)$  is defined as  $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$ . The *length of a line segment* is defined as the euclidian distance between the end points. The *length of a polyline* is defined as the sum of the individual line segment lengths.

## 2.3 The Relationship Between Drawing Models

Box drawings, straight-line and polyline drawings are the drawings of interest in this thesis. They stand in relation to each other in the following way:

A straight-line drawing is a polyline drawing with no bends by definition. Every sequence of line segments is of length 1.

A box drawing can be transferred to a polyline drawing with asymptotically the same area consumption. For this to happen, add empty grid lines until every segment of every edge has length at least 2. This will at most double the width and height. For any vertex, replace the box by an arbitrary grid point inside the box and reroute the incident edges to that vertex locally. Every box introduces a bend per edge, resulting in a polyline drawing with two bends and the asymptotically same area bound. [5, P. 145]

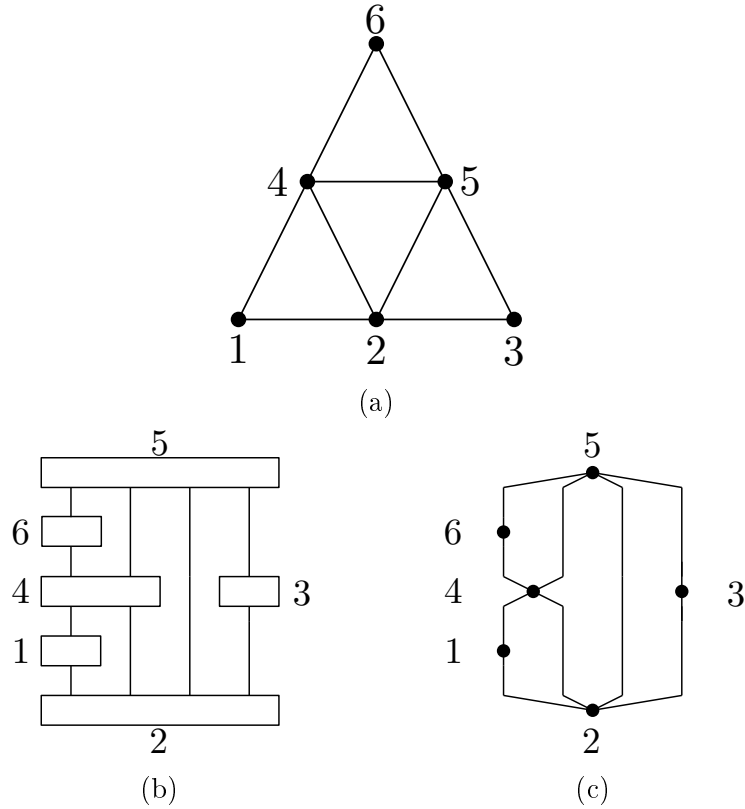


Figure 1: 1a is a straight-line drawing of a maximal outerplanar graph  $G$ , 1b is a box drawing of  $G$  and 1c is a polyline drawing derived from 1b

## 2.4 Graph Classes

### 2.4.1 Tree

A graph  $T$  is called *tree* if and only if it is connected, acyclic and undirected [7, P. 1172].

A tree is *rooted* if one of its vertices is distinguished from the other ones, called the *root*. Unless otherwise mentioned, it is assumed that every tree is rooted at the root vertex  $r$ .

When considering a path  $(r, v_1, \dots, v_k)$  from  $r$  to any other vertex  $v_k$ , then, the following holds:

1. Besides  $w$ , every vertex of this path is an *ancestor* of  $w$
2. For an edge  $(v_i, v_{i+1})$ ,  $v_i$  is called the *parent* of  $v_{i+1}$ , and  $v_{i+1}$  is a child of  $v_i$ .
3. The *height* of the root  $r$  is set to 0. For a vertex  $v$  of  $T$  it holds that its height is larger by one unit than its parent.

A vertex with no children is called a *leaf*. Any vertex which is not a leaf is called an *internal node*. A *level* of  $T$  consists of all vertices of the same height. The *height* of  $T$  is equal to the largest height of any vertex of  $T$ . [7, P. 1176ff]

### 2.4.2 $k$ -ary Tree

A  $k$ -ary tree is a rooted tree in which for every vertex has at most  $k$  children. A *complete  $k$ -ary tree* is a  $k$ -ary tree in which all leaves have the same height and all internal nodes have  $k$  children.

### 2.4.3 Outerplanar Graphs, Series Parallel Graphs and 2-Trees

An *outerplanar graph* is a planar graph that can be drawn without crossing in a way so that all vertices are on the outer face. A *maximal outerplanar graph* is an outerplanar graph to which it is not possible to add an edge without destroying the simplicity, planarity or outerplanarity property. A *2-terminal series-parallel graph* with terminals  $s, t$  is a recursively defined graph with one of the following three rules:

1. An edge  $(s, t)$  is a 2-terminal series-parallel graph
2. If  $G_i, i = 1, 2$ , is a 2-terminal series-parallel graph with terminals  $s_i, t_i$ , then in the serial composition  $t_1$  is identified with  $s_2$  to obtain a 2-terminal series-parallel graph with  $s_1, t_2$  as terminals
3. If  $G_i, i = 1, \dots, k$ , is a 2-terminal series-parallel graph with terminals  $s_i, t_i$ , then in a parallel composition we identify all  $s_i$  into one terminal  $s$  and all  $t_i$  into the other terminal  $t$  and the result is a 2-terminal series-parallel graph with terminals  $s, t$ .

A *series-parallel graph*, *SP-graph* in short, is a graph for which every biconnected component is a 2-terminal series-parallel graph. A SP-graph is *maximal* if no edge can be further added while maintaining a SP-graph. [5, P. 143ff]

A  $k$ -tree is a recursively defined graph with at least  $k + 1$  vertices. If  $n = k + 1$ , then the  $k$ -tree is the complete graph  $K_{k+1}$ . If  $n > k + 1$ , start with a  $K_{k+1}$  and every vertex added is adjacent to exactly  $k$  adjacent neighbours. The class of *2-trees* correspond to the class of maximal SP-graphs [1, Page 2].

## 2.5 Tools

### 2.5.1 SPQR Tree

A *cut vertex* in a graph  $G$  is a vertex whose removal disconnects  $G$ . A *separation pair* in  $G$  is a pair of vertices whose removal disconnects  $G$ . A *biconnected component* of  $G$  is a maximal (in terms of vertices and edges) biconnected subgraph of  $G$ . If  $G$  contains vertices  $s, t$ , then  $G$  is *st-biconnectable* if  $G \cup \{s, t\}$  is biconnected. A *split pair* of  $G$  is either a separation pair or a pair of adjacent vertices of  $G$ . A *maximal split component* of  $G$  in regard to a split pair  $\{u, v\}$  is either an edge  $(u, v)$  or a maximal subgraph  $G'$  of  $G$  such that  $G'$  contains  $u$  and  $v$  and  $\{u, v\}$  is not a split pair of  $G'$ . A vertex  $w$  aside from  $u$  and  $v$  belongs to exactly one maximal split component. A *split component* of  $\{u, v\}$  is defined as the union of any number of maximal split components of  $\{u, v\}$ . A split pair  $\{u, v\}$  is *maximal*, if there is no split pair  $\{w, z\}$  in  $G$  such that  $\{u, v\}$  is contained in a split component of  $\{w, z\}$ .

The *SPQR-Tree*  $\mathcal{T}$  of  $G$  is a recursively defined composition of  $G$  with respect to its split pairs.  $\mathcal{T}$  is a rooted tree with four types of nodes:  $S, P, Q$  and  $R$ .

Any node  $\mu$  of  $\mathcal{T}$  is related to a planar  $uv$ -biconnectible multigraph, the so-called *skeleton* of  $\mu$ , denoted as  $sk(\mu)$ .  $\mathcal{T}$  is recursively defined - Let  $(s, t)$  be an edge of  $G$ , called the *reference edge*.  $\mathcal{T}$  is initialized with a  $Q$  node  $\phi$  as root, representing the edge  $(s, t)$ . The skeleton of  $\phi$  consists of two parallel edges  $(s, t)$ . One is a *real* edge, one is a *virtual* edge.

After the initialization of  $\mathcal{T}$  with an arbitrary reference edge, consider a node  $\psi$  of  $\mathcal{T}$ ,  $G_\psi = (V(G), E(G) \setminus \{(s, t)\})$  and a pair of vertices  $\{u, v\}$  of  $G_\psi$ , called the *poles* of  $\psi$ .

**Trivial case** If  $G_\psi$  consists of a single edge  $(u, v)$ , then  $\psi$  is a  $Q$ -node. In this thesis, this case will be denoted as  $Q(u, v)$ .

**Series case** If  $G_\psi$  is not a single edge and not biconnected, then  $\psi$  is a  $S$ -node with at least one cut vertex  $c$  between the path between  $u$  and  $v$ . In this thesis, this case will be denoted as  $S(u, c, v)$ .

**Parallel case** If  $G_\psi$  is not a single edge, but biconnected with  $\{u, v\}$  as a split pair of  $G_\psi$ , then  $\psi$  is a  $P$ -node. In this thesis, this case will be denoted as  $P(u, v)$ .

**Rigid case** If  $G_\psi$  is not a single edge, biconnected with  $\{u, v\}$  not being a split pair of  $G_\psi$ , then  $\psi$  is a  $R$ -node. Due to the properties of the graph classes considered in this thesis, this case will not be covered in application and is not of further interest.

[2, P. 7-8]

### 2.5.2 Tree decomposition

Let  $G$  be a graph,  $T$  a tree, and let  $\mathcal{W} = (W_t)_{t \in T}$  be a family of vertex sets  $W_t \subseteq V_G$  indexed by the vertices  $t$  of  $T$ . The pair  $(T, \mathcal{W})$  is called a *tree decomposition* of  $G$  if it satisfies the following three conditions:

1.  $V_G = \bigcup_{t \in T} W_t$
2. For every edge  $e \in E_G$  there exists a  $t \in T$  such that both ends of  $e$  lie in  $W_t$
3. For all  $v \in V$ , there exists a connected subtree  $T'$  in  $T$  such that  $v \in W_{t'}, t' \in V_{T'}$

[8, P. 319]

The *width* of a tree decomposition is defined as

$$tw((T, \mathcal{W})) = \max\{|W_t|, t \in V_T\} - 1 \quad (1)$$

The *treewidth* of a graph is the least width of any tree decomposition of  $G$  [8, P. 321]. A graph with a treewidth bound by  $k$  is a  $k$ -tree [13, P. 5].

## 3 Initial Situation

### 3.1 The Fixed Edge-Length Planar Realization Problem

The *Fixed Edge-Length Planar Realization Problem*, *FEPR* problem in short, asks whether there exists a planar straight-line drawing of a given graph where the Euclidian length of an edge is given by a function  $\lambda : E(G) \rightarrow \mathbb{R}^+$ .

It was shown, that the *FEPR* problem is generally  $\mathcal{NP}$ -hard for triconnected graphs with unit lengths as well as biconnected graphs with unit lengths, with  $\lambda$  as a constant function. [1, P. 2]

### 3.2 Formalization Of The Problem

#### 3.2.1 The edge-length ratio

Let  $\Gamma_G$  be a given planar polyline drawing. The length of an edge is defined as the sum of  $k + 1$  line segments, induced by  $k$  bends.  $l_{\max}$  is the length of the longest edge in  $\Gamma_G$ ,  $\delta_{\min}$  is the minimal Euclidian distance between two adjacent vertices in  $\Gamma_G$ . Then, the edge-length ratio  $r$  of  $\Gamma_G$  is defined as:

$$r_{\Gamma_G} = \frac{l_{\max}}{\delta_{\min}} \quad (2)$$

It trivially holds, that  $r \geq 1$ , since the length of every polyline with at least one bend between two vertices is naturally longer than their respective Euclidian distance.  $r$  is said to be *optimal* if  $r = 1$ . Then, all the edges in a drawing are straight-lines and of the same length. This corresponds to the *FEPR* problem with  $\lambda$  being a constant function.

#### 3.2.2 Upper bound of the ratio

There exist multiple straight-line drawing algorithms which produce a drawing for a planar graph in area  $\mathcal{O}(n) \times \mathcal{O}(n)$ . Prominent examples are the Shift Method by Fraysseix, Pach and Pollack [17, P. 202ff] and Schnyder drawings [4, P. 3].

The area consumption of a straight-line drawing directly induces the bounds for the ratio. Let  $k \times k$  be the area consumption of a square bounding  $\Gamma_G$ ,  $k \in \mathcal{O}(n)$ . The maximal length of a straight-line is then bound by  $\sqrt{2}k$ , from one corner of the grid to the diagonal opposing one, while  $l_{\min}$  might value 1 UL. The ratio therefore values  $\sqrt{2}k \in \mathcal{O}(n)$  in the worst case.

This automatically gives an upper bound for any poly-line drawing  $\Gamma_G$  since a straight-line drawing can be seen as a polyline drawing with zero bends. Including bends in a straight-line drawing enables the possibility to reposition vertices in order to maximize the Euclidian distances even further.

### 3.3 On the edge-length ratio of maximal series-parallel graphs

The class of maximal SP-graphs is of particular interest in this thesis due to their balance in restricted properties on the one hand, and having non-trivial

approaches and results for general problems on the other hand. Maximal SP-graphs are biconnected, but not triconnected. This property implies a high amount of possible embeddings for a given maximal SP-graph  $G$ , since parallel subgraphs can be permuted and flipped. Therefore, finding drawings with an optimization regarding a specific problem require combinatorial and algorithmic approaches. This effect is pointed out by previous results regarding the edge-length ratio. It was shown that the *FEPR* problem is  $\mathcal{NP}$ -hard for straight-line drawings for maximal SP-graphs with up to four distinct edge lengths while it is solvable in linear time for uniform edge lengths [1, P. 1].

Also, it was proven that the ratio of straight-line drawings of maximal SP-graphs is unbounded, meaning, that for a given constant  $r$ , there exists a sufficiently large maximal SP-graph  $G$  with  $r_G > r$  over all its straight-line drawings. One result states that the ratio lies in the gap between the lower bound  $\Omega(\log n)$  and the upper bound  $\mathcal{O}(n^{0.695})$  [6, P. 2].

### 3.4 The Symposium Challenge

The *Live Challenge* takes place during the Graph Drawing Symposium in 2022. During one hour, teams will compete either manually or automatically with their own tools and implementation. The goal is to optimize the ratio for given graphs on a fixed grid. The team with the highest score achieved regarding the edge-length ratio wins. For teams participating with their own tools, an embedding might not be given with the input. For participants working manually, an embedding is already given beforehand.

For the automatic section of the Live Challenge, the input consists of a JSON file with the following entries:

**nodes** Every node has an unique ID value between 0 and the amount of nodes - 1, a value for the  $x$  and  $y$  coordinate each, delimited by the width and height

**edges** Every edge has an ID for source and destination each and an optional list of bend points, specified in  $x$  and  $y$  coordinate

**width (optional)** The maximum  $x$ -coordinate of the grid. If unspecified, the width is set to 1,000,000.

**height (optional)** The maximum  $y$  coordinate of the grid. If unspecified, the height is set to 1,000,000.

**bends** The maximum number of bends allowed per edge

The results of the optimization are also JSON files. The planarity of the graph shall be preserved and the ratio minimized by relocation of the nodes and using suitable bend points.

The Live Challenge addresses the practical aspects of a specific optimization task, including implementing heuristics and testing them beforehand. For the task at hand, the grid is fixed in order to keep a specific area consumption for given planar graphs while maximizing the Euclidian distance between adjacent vertices. In contrast to the Live Challenge, this thesis as a theoretical



---

piece of work addresses approaches to guarantee asymptotic upper bounds for the ratio of drawings regarding certain graph classes. The area consumption will be investigated in asymptotic behaviour while maximizing the Euclidian distances between vertices.

## 4 Trees

When analyzing a general problem of graph drawings, the class of trees is of interest due to their assessable properties. The first graph class considered for minimizing the ratio in a drawing is therefore the class of  $k$ -ary trees. The results of this class of trees will be applicable to any rooted tree. This section describes a drawing algorithm for a  $k$ -ary tree  $T$ , guaranteeing a nearly optimal Euclidian ratio in the resulting drawing  $\Gamma_T$ . The total area of  $\Gamma_T$  will depend on the height of  $T$ .

Trees are connected and acyclic per definition, inheriting exactly  $n - 1$  edges. These properties make trees accessible for a straightforward solution for a given problem.

When working on other graph classes, it may be possible to find an approach by reducing a graph  $G$  to an instance of a tree. In fact, the resulting drawing algorithm for  $k$ -ary trees in this section will serve as a first approach for drawing maximal outerplanar graphs in the succeeding section.

### 4.1 Properties Of Complete $k$ -ary Trees

**Lemma 1.** *Any tree  $T$  can be interpreted as a  $k$ -ary tree.*

A tree  $T$  does not necessarily inherit a root but any vertex of  $T$  can be flagged as such. The height of any vertex is then described as the path length starting from the root and  $k$  is set to the maximum amount of children of all the inner nodes.  $T$  is now rooted and  $k$  fixed, hence a  $k$ -ary tree. When describing a tree  $T$  as a  $k$ -ary tree, the root will be chosen so the resulting height is minimal.

**Lemma 2.** *The height  $h$  of a complete  $k$ -ary tree  $T$  is in  $\mathcal{O}(\log n)$ .*

*Proof.*

$$n = \sum_{i=0}^h k^i = \frac{k^{h+1} - 1}{k - 1} \quad (3)$$

$$\Leftrightarrow h = \log_k((k - 1)n + 1) - 1 \quad (4)$$

$$= \frac{\log((k - 1)n + 1)}{\log k} - 1 \quad (5)$$

$$\underbrace{\Rightarrow}_{k \text{ fixed}} h \in \mathcal{O}(\log n) \quad (6)$$

□

### 4.2 Drawing Algorithm For Complete $k$ -ary Trees

**Theorem 1.** *There exists a linear-time drawing algorithm which produces a planar straight-line drawing for complete  $k$ -ary trees with a nearly optimal ratio, apart from a rounding error, on area  $\mathcal{O}(n^2 \log n)$ .*

*Proof.* The following drawing will be constructed from top to bottom, meaning that the  $y$ -coordinates of the children of any vertex  $v$  are smaller than the  $y$  coordinate of  $v$ .

Let  $r := k^h$ . For a vertex  $v$  in height  $i$ , consider  $k$  equidistant columns with  $x$ -coordinates between  $x(v) - (k-1) \cdot k^{h-h'-1}$  and  $x(v) + (k-1) \cdot k^{h-h'-1}$ . These are integer coordinates since the distance between two columns next to each other equals  $2 \cdot \frac{k^{h-i}}{k}$ . Draw a circle around  $v$  with radius  $r$ . Choose the grid points  $v_i$  on the column closest to the resulting intersections with the constraint that  $y(v_i) \leq y(v)$  and connect  $v$  with its  $k$  children with a straight-line.

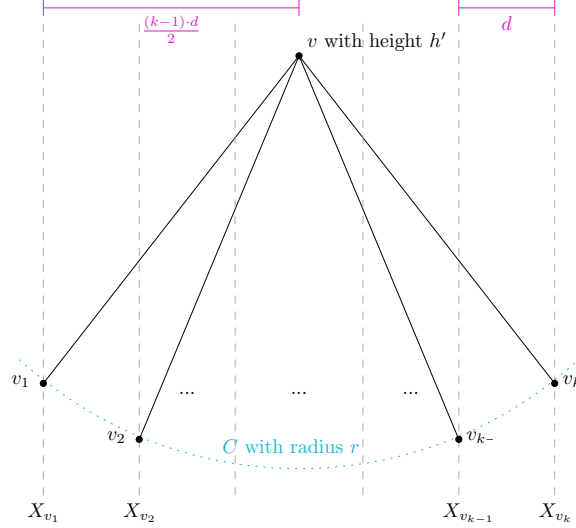


Figure 2: Illustration of drawing algorithm at a vertex  $v$  with height  $h$

The distance between two neighbouring columns in height  $i$  suffices for the remaining drawing since it holds for the remaining heights:

$$\underbrace{2 \cdot \sum_{j=i}^{h-1} k^{h-j-1}}_{\text{drawn from both columns}} = 2 \cdot \sum_{z=0}^{h-i-1} k^z \quad (7)$$

$$= 2 \cdot \frac{k^{h-i} - 1}{k - 1} < 2 \cdot k^{h-i} \quad (8)$$

The height of the drawing is bound by  $h \cdot r = h \cdot k^h \in \mathcal{O}(n \cdot \log n)$ . The width is bounded by  $2 \cdot \sum_{i=0}^h k^i = 2 \cdot \frac{k^{h+1}-1}{k-1} \in \mathcal{O}(n)$ , resulting in  $\mathcal{O}(n^2 \log n)$  area. Since the algorithm works from top to bottom and for height  $i$ , the area for every subtree is disjointedly reserved, the resulting drawing is planar. Furthermore, all straight-line edges inherit a length of approximately  $k^h$ . A rounding error bound by  $\varepsilon, 0 \leq \varepsilon < 1$  occurs when placing the vertices on grid points. The rounding error does not accumulate since the length  $r$  is fixed and the vertices are placed in the grid independently from each other. No bends were used and the ratio is bound by  $1 + \varepsilon$ .  $\square$

The following drawing algorithm sums up the approach described above.

---

**Algorithm 1:** Draw\_ $k$ -ary\_tree( $T$ )

---

**Input:** complete  $k$ -ary tree  $T$ ,  $h$

**Output:** Straight-line drawing of  $T$  with nearly optimal ratio

```

1  $h \leftarrow$  height of  $T$ 
2  $r \leftarrow k^h$ 
3 Draw  $root(T)$  on any grid point
4 Draw_ $k$ -ary_Children( $root(T)$ ,  $r$ ,  $h$ )
5 return  $\Gamma$ 
```

---



---

**Algorithm 2:** Draw\_ $k$ -ary\_Children( $v$ ,  $r$ ,  $h$ )

---

**Input:** Already drawn vertex  $v$ , radius and height  $r, h \in \mathbb{N}$

**Output:** Coordinates of all the children of  $v$

```

1 if  $v$  leaf then
2   return
3 else
4    $h' \leftarrow$  height( $v$ )
5    $d \leftarrow 2 \cdot k^{h-h'-1}$ 
6    $C \leftarrow \Gamma.DrawCircle(r, v)$ 
   /* Draw circle with radius  $r$  around  $v$  */
7   for  $i \in [1..k]$  do
8      $x(v_i) \leftarrow x(v) - \frac{(k-1) \cdot d}{2} + (i-1) \cdot d$ 
   /*  $x$ -coordinate of  $i$ -th child of  $v$  */
9      $X \leftarrow \Gamma.Column(x(v_i))$ 
   /* Identify the column at position  $x(v_i)$  */
10     $s \leftarrow \Gamma.Intersection(I, X)$ 
   /* Calculate the intersection of the circle  $C$  and the
      column  $X$  */
11     $y(v_i) \leftarrow round(y(s))$ 
12     $\Gamma.DrawStraightLine(v, v_i)$ 
13     $\Gamma.Draw_k\text{-ary_Children}(v_i, r, h)$ 
```

---

### 4.3 Drawing Algorithm For General Trees

**Theorem 2.** Any tree  $T$  admits a optimal straight-line drawing, apart from a rounding error, on exponential area.

*Proof.* By Lemma 1, any tree  $T$  can be interpreted as a  $k$ -ary tree. The algorithm 1 can be reused in order to produce a nearly-optimal straight-line drawing. Set the root  $r \in V(T)$  so that the height of  $T$  is minimal. Set  $k$  as the maximum amount of children of all inner nodes of  $T$ . The drawing algorithm 1 is slightly modified which checks the existence of any vertex since any  $k$ -ary subtree with height  $h$  is a subtree of a complete  $k$ -ary subtree of the same height. The output will be a nearly-optimal straight-line drawing  $\Gamma_{T'}$ . Removing the marked vertices will not alter the ratio or area consumption and the result is a nearly-optimal straight-line drawing  $\Gamma_T$ .

□

The following drawing algorithm sums up the approach for a general tree  $T$ .

---

**Algorithm 3:** Drawing algorithm for a tree  $T$

---

**Input:** A tree  $T$   
**Output:** Straight-line drawing  $\Gamma_T$  with nearly-optimal ratio

```

1 root  $\leftarrow v \in V(T)$  with minimal height for  $T$ 
2  $k \leftarrow 0$  for inner node  $v$  of  $T$  do
3   if  $v.Children.size() > k$  then
4      $k \leftarrow v.Children.size()$ 
5  $h \leftarrow$  height of  $T$ 
6  $r \leftarrow k^h$ 
7  $\Gamma.DrawVertex(root)$ 
   /* Draw  $root(T)$  on any grid point */
8  $\Gamma.DrawChildren(root, r, h)$ 
9 return  $\Gamma$ 

```

---



---

**Algorithm 4:** DrawChildren( $v, r, h$ )

---

**Input:** Already drawn vertex  $v$ , radius and height  $r, h \in \mathbb{N}$   
**Output:** Coordinates of all the children of  $v$

```

1 if  $v$  leaf then
2   return
3 else
4    $h' \leftarrow$  height( $v$ )
5    $d \leftarrow 2 \cdot k^{h-h'-1}$ 
6    $C \leftarrow \Gamma.DrawCircle(r, v)$ 
7    $q \leftarrow v.Children.size()$ 
   /* Draw circle with radius  $r$  around  $v$  */
8   for  $i \in [1..q]$  do
9      $x(v_i) \leftarrow x(v) - \frac{(k-1) \cdot d}{2} + (i-1) \cdot d$ 
       /*  $x$ -coordinate of  $i$ -th child of  $v$  */
10     $X \leftarrow \Gamma.Column(x(v_i))$ 
       /* Identify the column at position  $x(v_i)$  */
11     $s \leftarrow \Gamma.Intersection(I, X)$ 
       /* Calculate the intersection of the circle  $C$  and the
          column  $X$  */
12     $y(v_i) \leftarrow round(y(s))$ 
13     $\Gamma.DrawStraightLine(v, v_i)$ 
14     $\Gamma.Draw\_Children(v_i, r, h)$ 

```

---

## 4.4 Example Drawings

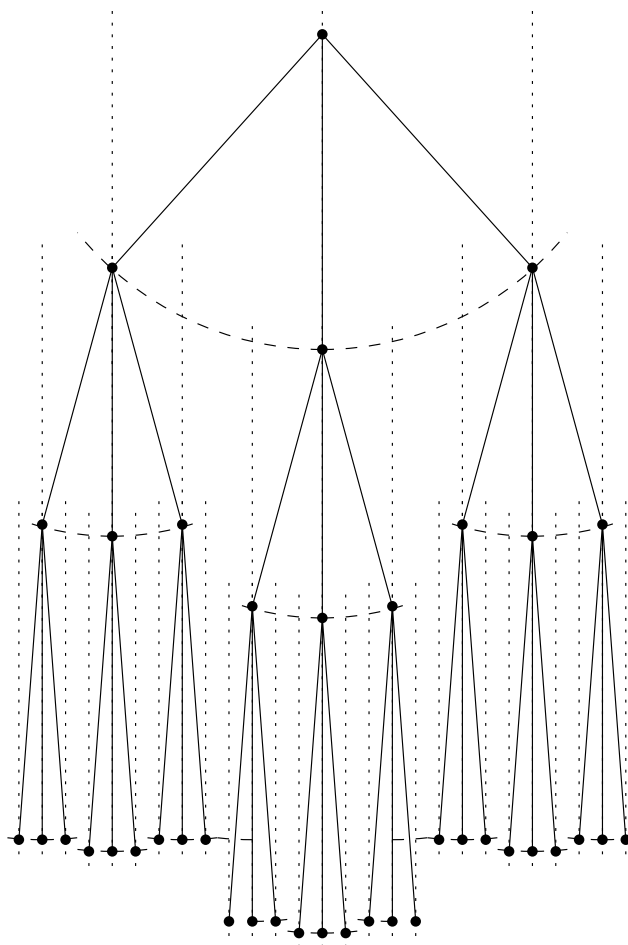


Figure 3: Ternary tree with height 3

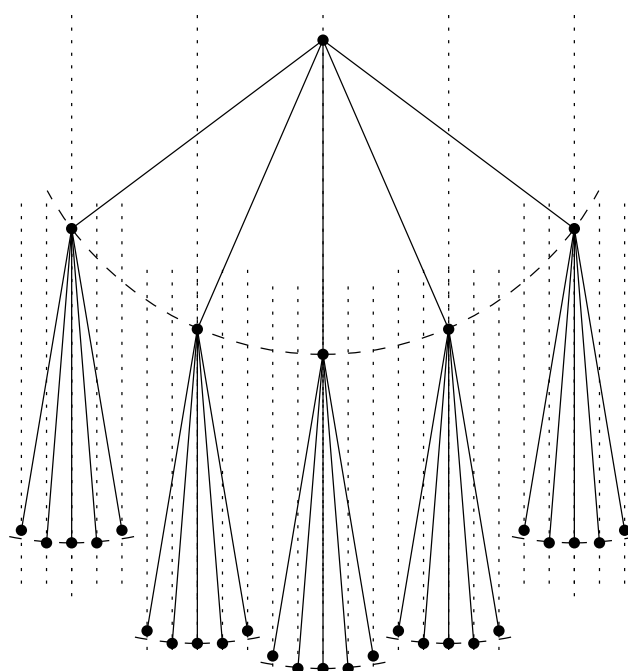


Figure 4: 5-ary tree with height 2

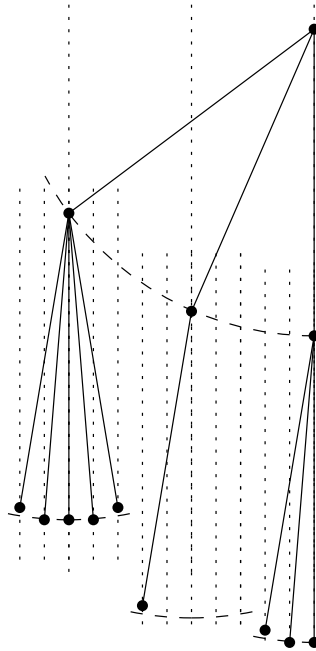


Figure 5: A rooted tree with at most 5 children per inner node

## 4.5 Implementation

The drawing algorithm for complete  $k$ -ary trees as described in this section got implemented as a script in `Python`. The `networkx` library was used to represent the graph structure. For creating a drawing, the `matplotlib` library came in handy since it allows explicit coordinate placements of vertices and a fixed aspect ratio of the resulting drawing.

The script consists of a `main` function and the drawing implementation of algorithm 1. It is possible to set the  $k$  and the height when calling the script by command-line arguments. The `main` function evaluates those command-line arguments and calls the recursive coordinate calculations starting from the root vertex with its coordinate  $(0,0)$ . All coordinates are rounded to integers in order to produce a straight-line drawing on a grid by default. Afterwards, the map between vertices and their coordinates are forwarded to an instance of the `matplotlib` plot. The output of the script consists of a straight-line drawing, the length of the shortest and longest edge and the ratio of the drawing.

For a full documentation of the implementation, the reader is invited to check-out the `git` repository found on GitHub<sup>©</sup>[14].

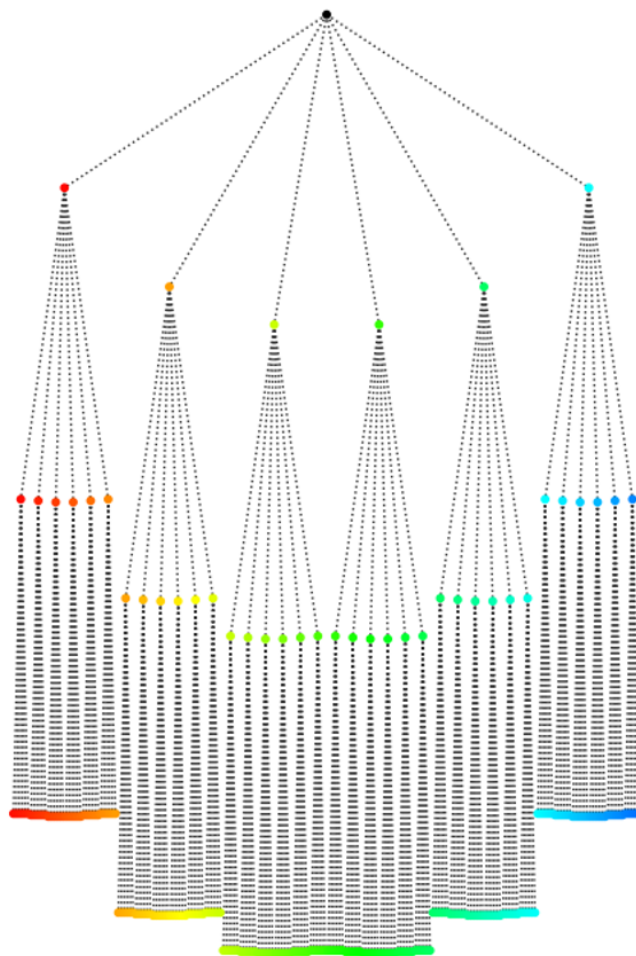


Figure 6: Output drawing of a 6-ary tree of height 3.  $l_{\min}$  values 215.75,  $l_{\max}$  values 216.09. The ratio values 1.0015777



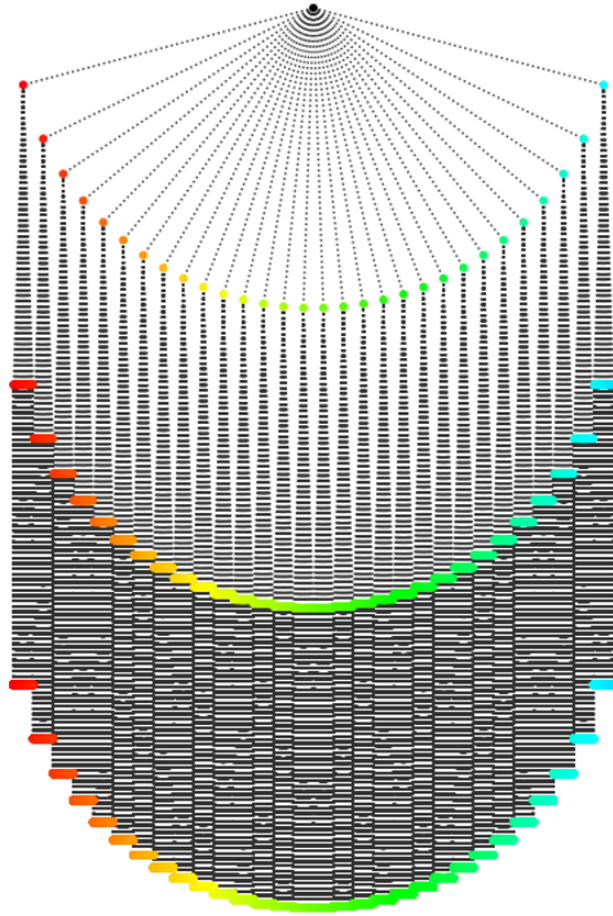


Figure 7: Output drawing of a 30-ary tree of height 3.  $l_{\min}$  values 26999.64,  
 $l_{\max}$  values 27000.45. The ratio values 1.00002984

## 5 Maximal Outerplanar Graphs

This section will address two main approaches of ratio minimization for drawings of maximal outerplanar graphs. Every outerplanar graph can be extended to a maximal outerplanar by inserting edges and preserving the outerplanarity property. Any outerplanar graph can then be drawn using a drawing algorithm for maximal outerplanar graphs by inserting edges and removing those after the drawing has been computed. Since any maximal outerplanar graph is a maximal SP-graph, the class of maximal outerplanar graphs is a strict subclass of the maximal SP-graphs and it will be determined whether one of the approaches was suitable to be extended for maximal SP-graphs, which will be the case for the second approach.

The first approach will address drawing a maximal outerplanar graph based on drawing its weak dual graph. The weak dual graph of an outerplanar graph is a tree and it is already known that any tree admits a nearly-optimal straight-line drawing. The second approach will create a layered box drawing of a maximal outerplanar graph which will then be transferred to a polyline drawing. It will be exposed that the second approach will produce polyline drawings with reasonable area consumption and will be extendable for general SP-graphs.

### 5.1 Properties Of Maximal Outerplanar Graphs

**Lemma 3.** *A maximal outerplanar graph  $G'$  inherits triangles as inner faces, except for the outerface.*

**Lemma 4.** *The weak dual graph  $G'^*$  of a maximal outerplanar graph  $G'$  is a simple tree with maximum degree 3 for any vertex.*

*Proof.* The weak dual graph  $G'^*$  is connected since  $G'$  is maximal outerplanar. Suppose, that  $G'^*$  contains a cycle  $\mathcal{C}$ . Then, there exists a vertex in  $G'$  which is enclosed from the outerface by faces according to  $\mathcal{C}$  in  $G'^*$  and  $G'$  is not outerplanar. This implies that  $G'^*$  must be acyclic and considering the connectedness,  $G'^*$  is a tree. Since any face  $f$  is a triangle, the degree of  $v_f$  in  $G'^*$  is at most three. The simplicity is derived from the maximal outerplanarity property. If there were multiple edges between vertex  $v_f$  and  $v_{f'}$  in  $G'^*$ , then there would be at least one vertex in  $G'$  which does not lie on the outerface.  $\square$

**Lemma 5.** *Let  $G'$  be a maximal outerplanar graph with  $n$  vertices and  $G'^*$  the dual graph excluding the outerface, a rooted tree with degree up to three for every vertex  $v_f$ . Then, the height of  $G'^*$  ranges between  $\Omega(\log n)$  and  $\mathcal{O}(n)$ .*

*Proof.* Since  $G'$  is a planar graph, it contains  $\mathcal{O}(n)$  faces. The rooted tree  $G'^*$  inherits the following property:

1. The root has at most three children
2. The subtrees rooted at the children of the root are binary trees

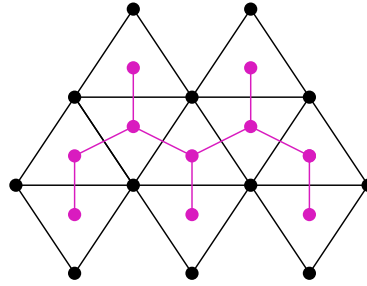
Placing  $\mathcal{O}(n)$  vertices in three binary trees connected to a root vertex results in a height of at least  $\Omega(\log n)$  due to the  $k$ -ary tree height property from Lemma 2. In the worst case,  $G'^*$  will be a chain of vertices, therefore a rooted tree with height  $\mathcal{O}(n)$ .  $\square$

**Lemma 6.** *A maximal outerplanar graph  $G'$  can be extended to a maximal outerplanar supergraph  $G^+$ .*

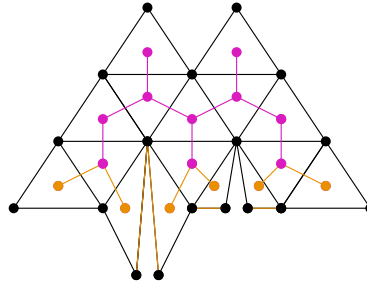
*Proof.* The vertex insertion works analogously to the recursive definition of a maximal SP-graph. A new vertex can be added by adding a new vertex  $v_f$  in the dual graph  $G^*$  so that the degree of  $G^*$  is still at most 3. The newly created face  $f$  must lie on the outerface and must be a triangle. Otherwise, the outerplanarity property is destroyed.  $\square$

**Observation 1.** *Let  $G'$  be a maximal outerplanar graph with a straight-line drawing  $\Gamma_{G'}$  and a ratio  $r$ . When  $G'$  is extended to a maximal outerplanar supergraph  $G'^+$ , the ratio  $r_{G'^+}$  increases regarding  $\Gamma_{G'^+}$  based on  $\Gamma_{G'}$ .*

When  $G'^*$  inherits a height of  $\mathcal{O}(\log n)$ , a new problem for a drawing emerges. When starting drawing the root of  $G'^*$ , new vertices are added in all directions, enclosing more and more area along the iterative drawing, as illustrated in the following figures:



(a) A straight-line drawing of a maximal outerplanar graph  $G$  with its weak dual graph magenta-colored. The ratio is optimal



(b) Extending  $G$  results in a ratio increase due to area restrictions, colored in orange

Figure 8: Illustration of area restriction for dense maximal outerplanar graphs

This results in short Euclidian distances relative to the longest edge, increasing the ratio.

## 5.2 Drawing Algorithm For Complete Outerplanar Graphs With One Bend

The first approach of a drawing algorithm addresses a ratio optimization for maximal outerplanar graphs whose weak dual graph is a rooted tree inheriting

logarithmic height. These class of maximal outerplanar graphs are described with help of properties regarding the weak dual graph in the following way.

**Definition 1.** *A maximal outerplanar graph is called complete if its weak dual graph  $G'^*$  fulfills these properties:*

1. *The root vertex has exactly three children.*
2. *Every other inner node has exactly two children. In other words, the subtrees adjacent to the root vertex are complete binary trees.*

A given maximal outerplanar graph can be drawn by using a drawing algorithm for its weak dual graph. In section 4, we describe a drawing algorithm for  $k$ -ary trees that produces a nearly-optimal straight-line drawing. The drawing algorithm 1 can be used with a minor modification to draw the weak dual graph of any complete maximal outerplanar graph  $G$ , since  $G'^*$  is a subtree of a ternary tree with the same height.

---

**Algorithm 5:** DrawOuterWeakDual( $G'$ )

---

**Input:** A complete maximal outerplanar graph  $G'$

**Output:** Straight-line drawing  $\Gamma_{G'^*}$  with nearly optimal ratio

```

1  $G^* \leftarrow$  weak dual graph of  $G$  with minimal height
2  $h \leftarrow \text{height}(G'^*)$ 
3  $\text{root} \leftarrow G'^*. \text{root}$ 
4 Draw( $\text{root}$ )
5 Draw_3-ary_Children( $\text{root}, 3^h, 1$ )
6 for  $v \in \text{root.children}$  do
7   Draw_2-ary_Children( $v, 2^{h-1}, h-1$ )
8 return  $\Gamma$ 
```

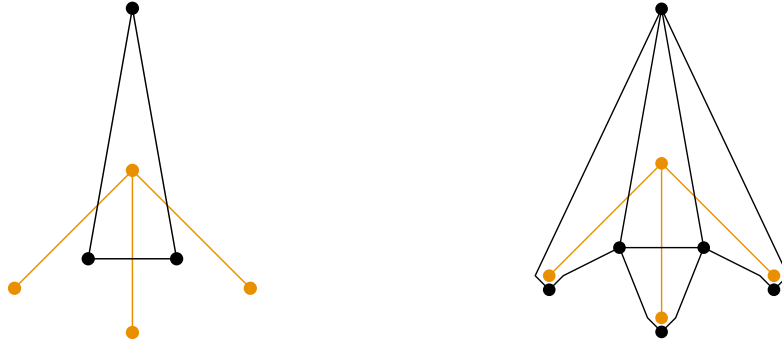
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Algorithm 5 produces a nearly optimal straight-line drawing for the weak dual graph of a complete outerplanar graph  $G'$ . The resulting drawing  $\Gamma_{G'^*}$  provides assistance to draw the complete outerplanar graph  $G'$ . Every vertex of  $\Gamma_{G'^*}$  serves as an anchor point for the drawing of its corresponding face in  $G'$ .

Starting at the root of  $G^*$ , a triangle is drawn around the root in a way, that each edge of  $G^*$  from the root to its three children crosses exactly one edge of the corresponding triangle face in  $G'$ . The vertices for the triangle are placed as follows. The first vertex lies above the already drawn root with an Euclidian distance to the root sufficiently high in order to preserve planarity for the remaining drawing. The other two vertices are placed inbetween the two triangles defined by the root, its {left, right} and middle children.

In order to guarantee a valid vertex and bend placement at every inner node  $v^*$ , the drawing is stretched horizontally and vertically by a factor of three.

Then, the drawing algorithm iterates over the height of  $G'^*$ . For every vertex  $v^*$  of height  $i \in \{1, \dots, h\}$  in  $G'^*$ , two bend points are placed 1 UL left and right from  $\Gamma_{G'^*}(v^*)$ , and the new vertex  $v$  is placed 1 UL below from  $\Gamma_{G'^*}(v^*)$ .



(a) Inserting the triangle around the root of  $G'^*$  (b) Placing vertices and having one bend per edge preserves outerplanarity

Figure 9: Scheme of creating a polyline drawing of a complete maximal outerplanar graph based on a straight-line drawing of its weak dual graph

$v^*$  is adjacent to an edge  $e^*$  defined in  $G^*$  that is crossing exactly one edge  $e = (v_1, v_2)$  of  $G'$ . This crossing corresponds to the vertices defining the new face,  $\{v, v_1, v_2\}$ . Since  $G'^*$  consists of three complete binary subtrees connected to the root, using the bends to draw the new face will preserve outerplanarity since the coordinate of every inner node inherits its unique  $x$  value by construction of algorithm 1 and every vertex lies on the outer face. This drawing approach

is summarized in the following algorithm.

---

**Algorithm 6:** DrawCompleteOuterplanar( $G'$ )

---

**Input:** Complete outerplanar graph  $G'$

**Output:** Polyline drawing  $\Gamma_{G'}$  with one bend per edge and ratio

$\mathcal{O}(\log n)$

```

1  $\Gamma \leftarrow \text{DrawOuterWeakDual}(G')$ 
2  $h \leftarrow \text{height}(G'^*)$ 
3 for  $v^* \in G'^*$  do
4    $x(v^*) \leftarrow 3 \cdot x(v^*)$ 
   /* Draw the triangle face around the root of  $G'^*$  */
5  $root \leftarrow \Gamma(G^*.root)$ 
6  $l \leftarrow \Gamma(G^*.root.leftChild)$ 
7  $m \leftarrow \Gamma(G^*.root.middleChild)$ 
8  $r \leftarrow \Gamma(G^*.root.rightChild)$ 
9  $v_1 \leftarrow \Gamma.\text{PlaceVertex}(x(root), y(root) + h \cdot 3^h)$ 
10  $v_2 \leftarrow \Gamma.\text{PlaceVertex}(\frac{x(root)+x(l)+x(m)}{3}, \frac{y(root)+y(l)+y(m)}{3})$ 
11  $v_3 \leftarrow \Gamma.\text{PlaceVertex}(\frac{x(root)+x(m)+x(r)}{3}, \frac{y(root)+y(m)+y(r)}{3})$ 
12  $\Gamma.\text{DrawLineSegment}(v_1, v_2)$ 
13  $\Gamma.\text{DrawLineSegment}(v_1, v_3)$ 
14  $\Gamma.\text{DrawLineSegment}(v_3, v_2)$ 
   /* Iterate over the height to draw the remaining vertices of  $G'$  */
15 for  $i \in [1..h]$  do
16   for  $v^* \in G^*$  with height  $i$  do
17      $b_l \leftarrow \Gamma.\text{PlaceBendPoint}(x(v^*) - 1, y(v^*))$ 
18      $b_r \leftarrow \Gamma.\text{PlaceBendPoint}(x(v^*) + 1, y(v^*))$ 
19      $v \leftarrow \Gamma.\text{PlaceVertex}(x(v^*), y(v^*) - 1)$ 
20      $e^* \leftarrow (v^*, \text{parent}(v^*))$ 
21      $e \leftarrow (v_1, v_2)$  edge intersecting  $e^*$  // w.l.o.g.  $v_1$  ordered left
       of  $v_2$ 
22      $\Gamma.\text{DrawLineSegment}(v, b_l)$ 
23      $\Gamma.\text{DrawLineSegment}(b_l, v_1)$ 
24      $\Gamma.\text{DrawLineSegment}(v, b_r)$ 
25      $\Gamma.\text{DrawLineSegment}(b_r, v_2)$ 
26  $\Gamma.\text{delete}(G'^*)$ 
27 return  $\Gamma$ 

```

---

### 5.2.1 Analysis

**Theorem 3.** *Every complete outerplanar graph  $G'$  admits a polyline drawing  $\Gamma_G$  on  $\mathcal{O}(n^2 \log n)$  area with one bend per edge, preserving outerplanarity. The drawing is constructed in linear time and the ratio lies in  $\mathcal{O}(\log n)$ .*

*Proof.* The triangle around the root of  $G^*$  consists of a vertex  $v_1$  placed atop of the root vertex with distance  $h \cdot r^h$  and two vertices  $v_2, v_3$  placed at the centroids of the triangles defined by  $\{\text{root}, \text{root.leftChild}, \text{root.middleChild}\}$  and  $\{\text{root}, \text{root.middleChild}, \text{root.rightChild}\}$ . The placement of the vertices  $v_1, v_2$  and  $v_3$  guarantee exactly one intersection between an edge of  $G'$  and an

edge of  $G'^*$  in  $\Gamma$ .

After stretching the drawing horizontally by a factor of three, there exist free grid points next to every vertex of  $G'^*$  which guarantees a grid point placement left and right of any vertex  $v^*$ . During the iteration over the height starting at height 1, every intersection between an edge of  $G'^*$  and  $G'$  refer to vertices on the outerface and a new face of  $G'$  is attached on the outerface, preserving the outerplanarity of the drawing.

Since  $v_1$  is placed with a distance of  $h \cdot r^h$  atop of the root of  $G^*$  and  $v_2$  and  $v_3$  partition the  $x$  coordinate of the binary subtrees rooted at the children of the root of  $G^*$ , planarity is preserved.

The resulting area bounds are asymptotically the same compared to a drawing of a ternary tree since the width and the height are multiplied by a constant. The area consumption lies still in  $\mathcal{O}(n^2 \log n)$ .

The construction of  $G'^*$  with minimal height lies in  $\mathcal{O}(n)$  since there are  $\mathcal{O}(n)$  faces for any maximal outerplanar graph. Drawing  $G'^*$  and  $G'$  lies in  $\mathcal{O}(n)$ . The runtime of this algorithm is therefore in linear time.

The minimal Euclidian distance values at least  $2^h$  by construction of algorithm 1 and lies in  $\mathcal{O}(n)$ . The length of the longest polyline spans the whole height of the drawing and lies in  $\mathcal{O}(n \log n)$ . The ratio lies therefore in  $\mathcal{O}(\log n)$  since the height of  $G^*$  lies in  $\mathcal{O}(\log n)$ .  $\square$

### 5.2.2 Example Drawing

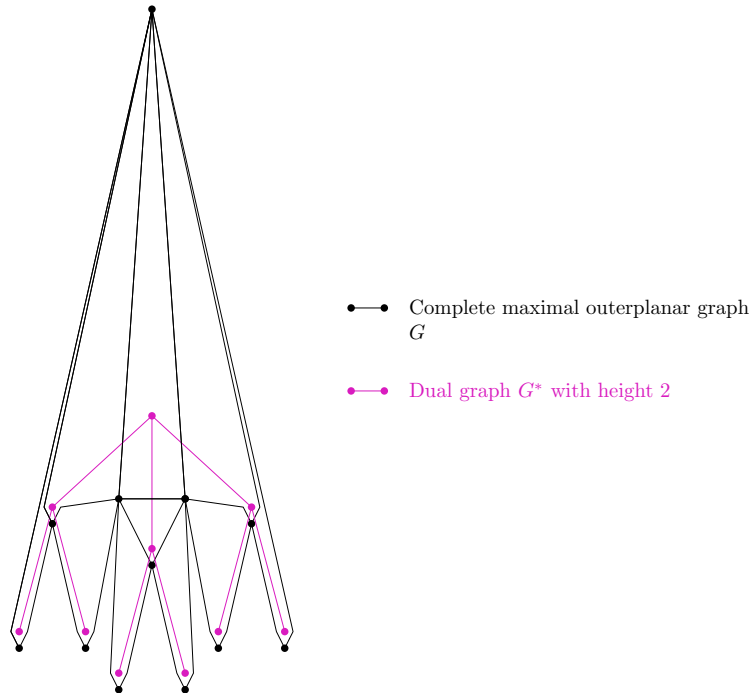


Figure 10: Polyline drawing of a complete outerplanar graph  $G'$ . The dual graph  $G'^*$  inherits a height of 2.

### 5.2.3 Limitations

As addressed by Observation 1, this algorithm works fine for a complete maximal outerplanar graph  $G'$  since then, the height of  $G'^*$  is bound by  $\mathcal{O}(\log n)$ .

On the other hand, when  $G'$  is not a complete maximal outerplanar graph, the height of  $G'^*$  might be of linear size. This would worsen the area bounds and the ratio of the resulting drawing drastically since the resulting height is determined by the height of  $G'^*$  multiplied by a factor of  $n$ . The ratio will become linear in the worst case on  $\mathcal{O}(n^3)$  area, which is worse compared to any well-established straight-line drawing algorithm producing a drawing on  $\mathcal{O}(n^2)$  area with a ratio of  $\mathcal{O}(n)$ . In addition, the drawing algorithm will only work for simple weak dual graphs. The weak dual graph of a maximal SP graph is a multigraph.

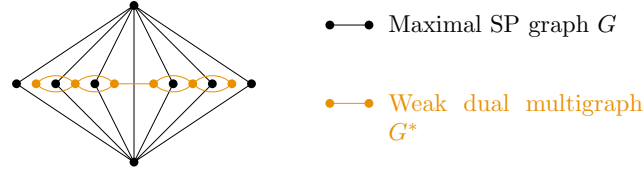


Figure 11: A maximal SP graph with its weak dual multigraph, colored in orange

The approach of drawing the weak dual graph at first followed by the outerplanar graph serves as an idea for a *layered drawing*. The resulting drawings are valid layerings since the vertices of  $G'$  added on a fixed height of  $G'^*$  are not adjacent. As already observed, a layered drawing algorithm might guarantee a reasonable ratio by defining a minimal distance between two layers and therefore between two adjacent vertices. Since drawing the weak dual graph is not applicable for SP-graphs, the *tree decomposition* of an SP-graph will serve as a guidance tool for the sequence of vertices drawn by a layering algorithm. The drawing algorithm will use the *SPQR tree* derived from a tree decomposition.

When analyzing upper bounds for the ratio of a drawing for a maximal outerplanar graph  $G'$ , it is crucial to take a look at the tree structure of its tree decomposition. The following definition describes the difference of a  $k$ -ary tree  $T$  to being a complete  $k$ -ary tree. This description of  $k$ -ary tree partitionings is very similar to a tree decomposition and will help during the analysis of a maximal outerplanar graph  $G'$  with its tree decomposition, since any tree decomposition is a  $k$ -ary tree.

### 5.3 Partitioning A $k$ -ary Tree In Complete $k$ -ary Subtrees

**Definition 2.** A partitioning  $P = (\mathcal{P}, \mathcal{W})$  of a  $k$ -ary tree  $T$  is defined with the following properties:

- For every vertex  $p$  in  $\mathcal{P}$  there exists a bag  $w$  in  $\mathcal{W}$
- Every bag  $w$  in  $\mathcal{W}$  contains a complete  $k$ -ary subtree of  $T$  and is non-empty
- If there exists an edge in  $T$  between two complete subtrees described by  $w_1$  and  $w_2$  out of  $\mathcal{W}$ , then  $p_1$  and  $p_2$  share an edge in  $\mathcal{P}$
- $\mathcal{P}$  is a rooted tree



A partition is a pair consisting of a vertex of  $\mathcal{P}$  and its corresponding bag  $\mathcal{W}$ . A partitioning  $P$  is minimal if every other partitioning  $P'$  of  $T$  contains a higher amount of partitions.

Let  $T$  be a rooted tree with  $n$  vertices. For a partitioning  $P$  covering all the vertices of  $T$ , the amount of bags of size  $\mathcal{O}(K)$  is bounded by  $\mathcal{O}(\frac{n}{K})$ , whereas  $K$  is bounded by  $n$ . Also, any combination of partitions are possible. Presuming that a partitioning covers  $\mathcal{O}(n)$  vertices of a graph, any combination of multiple partitionings of constant amount is possible. For example, let  $|V(G')| = 2n$ . One chain of  $\mathcal{O}(n)$  vertices followed by a complete binary tree with  $n$  vertices results in a legitimate rooted tree with height  $\mathcal{O}(n)$ . The minimal partitioning of this example consists of  $\mathcal{O}(n)$  partitions in total.

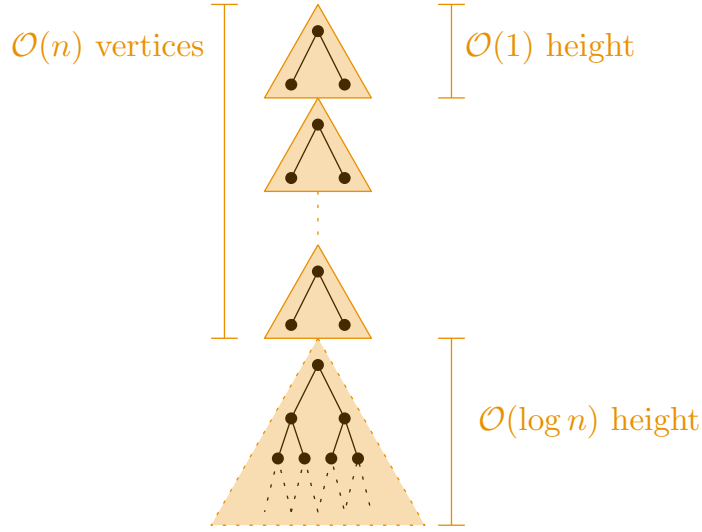


Figure 12: A rooted tree of  $\mathcal{O}(n)$  height partitioned in complete  $k$ -ary subtrees (in orange)

**Lemma 7.** *The height of  $G$  interacts with the minimal partitioning  $P$  of  $G$  in the following way:*

1. *If  $P$  consists of  $\mathcal{O}(n)$  many partitions of constant size, the height of  $G$  lies between  $\Omega(\log n)$  and  $\mathcal{O}(n)$*
2. *If  $P$  consists of  $\mathcal{O}\left(\frac{n}{\log n}\right)$  partitions of size  $\mathcal{O}(\log n)$ , then the height of  $G$  lies between  $\Omega\left(\log\left(\frac{n}{\log n}\right) \cdot \log \log n\right)$  and  $\mathcal{O}(n)$*
3. *If  $P$  consists of  $\mathcal{O}(\sqrt{n})$  partitions of size  $\mathcal{O}(\sqrt{n})$ , then the height of  $G$  lies between  $\Omega(\log^2 n)$  and  $\mathcal{O}(\sqrt{n} \log n)$*
4. *if  $P$  consists of a constant amount of partitions of size  $\mathcal{O}(n)$ , then the height is bound by  $\mathcal{O}(\log n)$ .*

*Proof.* Let  $T$  be a  $k$ -ary tree and  $P = (\mathcal{P}, \mathcal{W})$  its minimal partitioning. Without loss of generality, it is presumed that all partitions of  $P$  are of the same size. Since  $\mathcal{P}$  is a tree, the following extremal cases for  $\mathcal{P}$  are considered for the height of  $T$ :

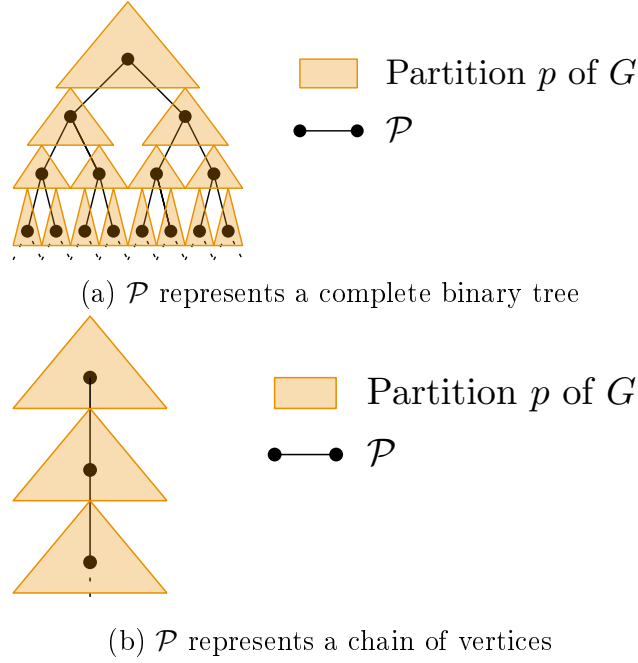


Figure 13: Extremal cases regarding the structure of  $\mathcal{P}$  of a partitioning  $\mathcal{P}$

One extremal case covers  $\mathcal{P}$  being a complete binary tree. By Lemma 2, for the height investigation of  $G$  it suffices  $\mathcal{P}$  to be binary since every complete  $k$ -ary tree has asymptotically the same height bound. The other extremal case covers a chain of vertices of  $\mathcal{P}$ . For case 13a,  $\mathcal{P}$  is a tree with height  $\mathcal{O}(\log |\mathcal{P}|)$  and up to  $\mathcal{O}(|\mathcal{P}|)$  height in case 13b.

1. A complete  $k$ -ary tree of constant size inherits a constant height. With  $|\mathcal{P}| \in \mathcal{O}(n)$ , substituting every vertex of  $\mathcal{P}$  with complete  $k$ -ary trees of constant height does not alter the height asymptotically and the height bounds are valid.
2. A complete  $k$ -ary tree with  $\mathcal{O}(\log n)$  vertices inherits a height of  $\mathcal{O}(\log \log n)$ . The height of  $\mathcal{P}$  lies in  $\mathcal{O}\left(\log\left(\frac{n}{\log n}\right)\right)$  for case 13a and  $\mathcal{O}\left(\frac{n}{\log n}\right)$  for case 13b. Therefore, the height of  $G$  lies in  $\mathcal{O}\left(\log\left(\frac{n}{\log n}\right) \cdot \log \log n\right)$  for case 13a and  $\mathcal{O}\left(\frac{n}{\log n} \cdot \log \log n\right)$  for case 13b.
3. If every vertex of  $\mathcal{P}$  represents a complete  $k$ -ary tree of height  $\mathcal{O}(\log \sqrt{n}) = \mathcal{O}(\log n)$ , the resulting total height of  $G$  is in  $\mathcal{O}(\log^2 n)$  for case 13a and in  $\mathcal{O}(\sqrt{n} \log n)$  for case 13b.
4. A constant multiple of  $\log n$  height for a vertex in  $\mathcal{P}$  results in a total height of  $\mathcal{O}(\log n)$  for  $G$ .

□

## 5.4 More Properties Of Maximal Outerplanar Graphs

**Lemma 8.** *Any maximal outerplanar graph  $G'$  has a tree decomposition  $(T', W')$  such that  $T'$  is of degree at most 3.*

*Proof.* Consider the weak dual graph  $G'^*$  considered in Definition 1. For vertices  $v_1^*, v_2^*$  in  $G'^*$ , insert vertices  $t_1, t_2$  in  $T$  which are adjacent if  $v_1^*, v_2^*$  are adjacent in  $G'^*$ . The corresponding bags  $w_1, w_2$  contain the vertices of  $G$  which define the face referred by  $v_1^*, v_2^*$  in  $G'^*$ .  $T$  is isomorphic to  $G'^*$  and therefore is of degree at most 3.  $\square$

**Lemma 9.** *Let  $v, w$  be any two adjacent vertices in a maximal outerplanar graph  $G$ . Then, the connected subtree  $T'$  of a tree decomposition of  $G$  containing both  $v$  and  $w$  contains at most two vertices.*

*Proof.* If  $T'$  would contain at least 3 vertices, then there would exist three distinct vertices in  $G$  forming a 3-clique with  $v$  and  $w$ , destroying the outerplanarity property of  $G$ .  $\square$

**Lemma 10.** *Let  $(T, W)$  be the tree decomposition of a maximal outerplanar graph  $G$ ,  $t_1, t_2, t_p \in V(T)$  and  $t_1, t_2$  are the children of  $t_p$ . Then, the following holds:*

1. *For  $i = 1, 2$ , the bags  $w_i$  and  $w_p$  share exactly two vertices*
2.  *$w_1$  and  $w_2$  share exactly one vertex*

*Proof.* 1. Since  $G$  is a maximal outerplanar graph and therefore a 2-tree, all bags contain exactly 3 vertices. Since  $t_p$  is the parent of  $t_1$ , their bags have two vertices in common when adding a vertex to two adjacent vertices of  $t_p$ .

2. This follows directly by Lemma 9.  $\square$

**Lemma 11.** *Let  $(T, W)$  be a tree decomposition of a given maximal outerplanar graph  $G$ . The subtree  $T'$  of  $T$  containing a vertex  $v$  of  $G$  is a path and of length  $\mathcal{O}(\text{height}(T))$ .*

Let  $t_p$  the parent of  $t_1, t_2$  and  $t_3$  and  $v \in w_p$ . Assume, that  $v \in w_1, w_2, w_3$ . Since the bags are of size three, there would be a vertex  $v' \in w_p$  such that the subtree of  $T$  containing  $v, v'$  contains more than two vertices, contradicting Lemma 9. Then, the subtree  $T$  containing  $v$  is of degree 2 and therefore a list.

**Definition 3.** *When traversing a tree decomposition  $(T, W)_G$  of a graph  $G$  with DFS, a vertex  $v \in V(G)$  is called active as soon as a vertex of the connected subtree  $T'$  of  $T$  containing  $v$  in its bags is explored during DFS. A vertex  $v \in V(G)$  is called finished if  $T'$  has been fully explored by DFS.*

**Lemma 12.** *Let  $G'$  be a maximal outerplanar graph and  $(T', W')$  its tree decomposition with  $h_{T'}$  as height of  $T'$ . When using DFS as graph traversal for a drawing algorithm of  $G'$ , a vertex  $v'$  of  $G'$  is active for at least  $\Omega(h_{T'})$  steps.*

*Proof.* This follows directly by Lemma 11.  $\square$

**Lemma 13.** *Let  $G'$  be a complete maximal outerplanar graph and  $(T', W')$  its tree decomposition. When traversing  $(T', W')$  by using DFS, there are at most  $\mathcal{O}(\log n)$  vertices active simultaneously.*

*Proof.* Let  $v' \in V(G')$  and  $T'_{v'}$  be the subtree of  $T'$ , containing  $v'$  in its bags. By Lemma 12,  $T'_{v'}$  is a chain of vertices. Since  $G'$  is maximal outerplanar, by Lemma 9 it holds that the amount of occurrences of any other vertex  $w' \in V(G') \setminus \{v'\}$  is bound by 2. Since  $G'$  is complete, the height of  $T'$  is bound by  $\mathcal{O}(\log n')$ .

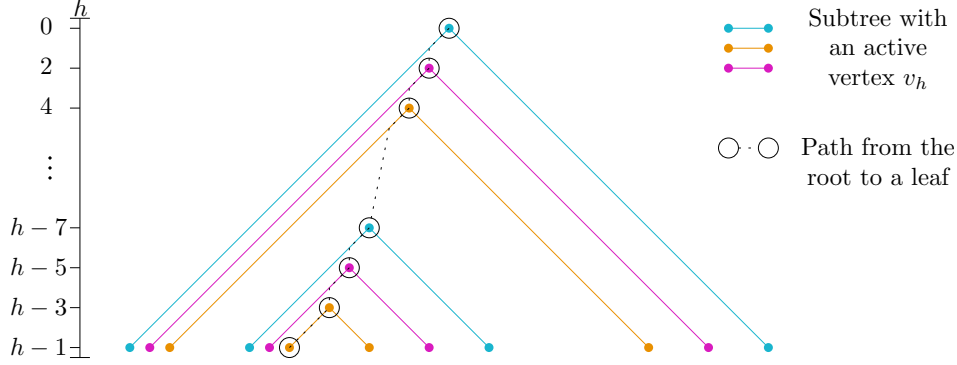


Figure 14: A complete binary tree with up to  $\mathcal{O}(\log n)$  active vertices for a DFS path

Let  $t'_r$  be the root and  $t'_l$  a leaf of  $T'$ . Then, the path  $p$  from  $t'_r$  to  $t'_l$  is unique. For every vertex  $p_i$  of  $p$ , at most one vertex is set to being active during the DFS graph traversal, when starting at  $t'_r$  up to  $t'_l$ . When  $t'_l$  is explored, there are at most  $\mathcal{O}(\log n')$  vertices still active. The following holds for  $p_i$  in  $p$ :

- If  $p_i$  is a leaf and explored, then the induced new active vertex  $v'_i \in V(G')$  is already finished since  $|V(T'_{v'_i})| = 1$ .
- If  $p_i$  is not a leaf, then all the active vertices induced by exploring  $p_j$  with  $j > i$  are finished first when using DFS.

This means that up to  $\mathcal{O}(\log n')$  vertices are active simultaneously when exploring  $T'$ .  $\square$

**Lemma 14.** *When prioritizing subtrees of minimal height while traversing any maximal outerplanar graph  $G'$  with DFS, then there are up to  $\mathcal{O}(\log^2 n')$  vertices active simultaneously.*

*Proof.* Let  $G'$  be a maximal outerplanar graph with and  $(T', W')$  be its tree decomposition. The height of  $T'$  is bound by  $\mathcal{O}(n')$ . Since the degree of any vertex in  $T'$  is at most 3, there are up to three binary trees connected to the root of  $T'$ . The minimal partitioning of the three binary subtrees  $P_i = (\mathcal{T}_i, \mathcal{W}_i)$  of  $T'$ ,  $1 \leq i \leq 3$ , consist of binary tree partitions and  $\mathcal{T}_i$  are binary trees.

Consider a minimal partitioning  $\mathcal{P}$  and a path  $\tilde{t} = (t_1, \dots, t_k)$  starting at the root and ending at a leaf of  $\mathcal{T}$ . When subtrees of minimal heights are prioritized during every step of the DFS of  $T$ , then it holds that by the time the DFS reached a partition  $t_j \in \tilde{t}$ , then all the other partitions  $t_i, i < j$  have been almost fully explored, leading to a constant amount of locally active vertices. In the case of  $P$  being a complete binary tree, the priority of the subtree with the smallest height does not take any effect. Considering Lemma 7, the largest upper bound for the height of  $T$  lies in  $\mathcal{O}(\log^2 n)$  when a minimal partitioning  $P$  consists of  $\sqrt{n'}$  partitions with  $\sqrt{n'}$  vertices per partition bag and  $\mathcal{T}$  being a complete binary tree. analogously to the proof of Lemma 13, traversing a path from the root of  $T$  to any leaf will set up to  $\mathcal{O}(\log^2 n')$  vertices active.  $\square$

## 5.5 Drawing Algorithm For Maximal Outerplanar Graphs With Two Bends

Based on the fact that a layering induced by the drawing algorithm 6 did improve the ratio for dense maximal outerplanar graphs, a new approach will create a box drawing with the layering property. Since every maximal outerplanar graph has triangles as interior faces, its treewidth is bound by 2.

In order to draw a maximal outerplanar graph  $G$ , its tree decomposition will be transferred to an  $SPQR$ -Tree.

**Lemma 15.** *There exists a function  $f : (T, W) \rightarrow \mathcal{T}$  which derives an  $SPQR$ -Tree out of a tree decomposition of a maximal SP-graph  $G$  with the following properties:*

1. *There is no  $R$  node in  $\mathcal{T}$*
2. *The skeleton of any serial node  $S$  consists of exactly three vertices  $s_1, s_2, s_3$*
3. *The asymptotic height of  $\mathcal{T}$  equals the asymptotic height of  $T'$*

*Proof.* Let  $G$  be an maximal SP-graph and  $(T, W)$  its tree decomposition. Let  $t_r$  be the root of  $T$ , representing a triangle of the vertices  $v_1, v_2, v_3$ . Its  $SPQR$ -Tree  $\mathcal{T}$  consists of three  $Q$  vertices, one for every edge of the triangle, one  $S$  node and one  $P$  node.  $\mathcal{T}$  is illustrated in the figure below:

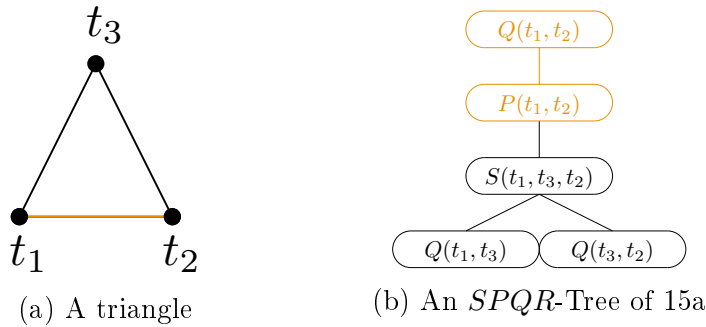


Figure 15: A triangle illustrated in figure 15a and its  $SPQR$ -Tree in figure 15b. The reference edge is marked in orange.

When traversing  $T$ , every newly explored vertex of  $T$  represents an addition of a new vertex of  $G$  to  $\mathcal{T}$ . Let  $v$  be the vertex of interest, adjacent to  $v_1$  and  $v_2$ .  $v_1$  and  $v_2$  are already part of  $\mathcal{T}$  and since the edge  $(v_1, v_2)$  exists, there is a  $Q$  node in  $\mathcal{T}$  representing this edge. This  $Q$  node is denoted as  $Q(v_1, v_2)$ . There are two cases to consider:

**Case 1:**  $Q(v_1, v_2)$  is adjacent to an  $S$  node

If  $Q(v_1, v_2)$  is part of a serial composition in  $\mathcal{T}$ , adding  $v$  will introduce a parallel composition around the split pair  $(v_1, v_2)$  between  $v$  and the residual graph  $G \setminus \{v_1, v_2\}$ . The following figure illustrates the insertion of  $v$  into  $\mathcal{T}$ :

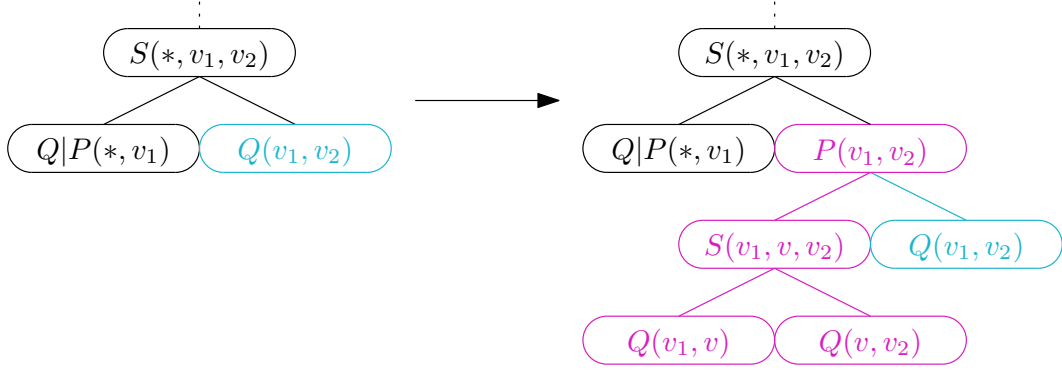


Figure 16: Insertion of a new vertex  $v$  when  $Q(v_1, v_2)$  is not attached to a  $P$  node)

**Case 2:**  $Q(v_1, v_2)$  is adjacent to  $P(v_1, v_2)$

Since there is already a parallel composition around the split pair  $(v_1, v_2)$ , inserting  $v$  will be a serial composition as illustrated in the following figure:

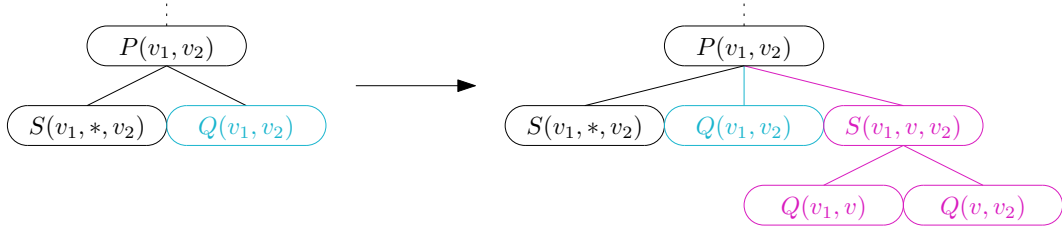


Figure 17: Insertion of a new vertex  $v$  when  $Q(v_1, v_2)$  is not attached to a  $P$  node)

Since  $G$  is a maximal SP-graph, there is not any  $R$  node in  $\mathcal{T}$  by definition. The second property holds as an invariant during the process of creating  $\mathcal{T}$  since it is true for any triangle and any new vertex insertion. Every vertex of  $T$  is substituted with a constant amount of vertices in  $\mathcal{T}$ , so the height of  $\mathcal{T}$  equals the height of  $T$  asymptotically.

So there exists a function  $f$  which derives an  $SPQR$ -Tree from a given tree decomposition with the stated properties.  $\square$

The drawing algorithm will transfer a tree decomposition  $(T', W')$  of a maximal outerplanar graph  $G'$  to an  $SPQR$ -Tree  $\mathcal{T}'$ . Afterwards, the algorithm explores  $\mathcal{T}'$  by DFS starting at the root node. This is achieved by a stack implementation in the pseudocode. For a vertex  $t' \in V(\mathcal{T}')$ , the child of  $t'$  which roots the subtree of minimal height will always be prioritized during the DFS. This combined strategy of DFS and subtree priority will exclude unnecessarily inserted new layers in the resulting box drawing for  $(T', W')$ .

The following pseudocode creates a box drawing for a given *SPQR*-Tree:

---

**Algorithm 7:** DrawSPQR( $\mathcal{T}$ )

---

**Input:** *SPQR*-tree  $\mathcal{T}$  of a graph  $G$

**Output:** Box drawing  $\mathcal{B}_G$

---

```

1 Stack stack
2 SPQRVerticesDone  $\leftarrow \emptyset$ 
3  $v \leftarrow \mathcal{T}.\text{root}$  stack.push( $\mathcal{T}.\text{root}$ )
4 column  $\leftarrow 0$ 
5  $\delta \leftarrow$  pairwise distance between layers
6 Lower Layer  $l_{low} \leftarrow 0$ 
7 Upper Layer  $l_{up} \leftarrow l_{low} + \delta$ 
8  $B.\text{DrawBox}(q_1, l_{up}, \text{column})$ 
9  $B.\text{DrawBox}(q_2, l_{low}, \text{column})$ 
10 ActiveVertices  $\leftarrow \{q_1, q_2\}$ 
11 while VerticesDone  $\neq V(\mathcal{T})$  do
12      $v \leftarrow \text{stack.pop}$ 
13     List children  $\leftarrow v.\text{children}$ 
14     children.SortByHeightOfSubtreesDescending
15     while children  $\neq \emptyset$  do
16         stack.push(head(children))
17         children.remove(head(children))
18     if  $v$  is  $Q$  node then ; //  $Q$  node refers an edge  $(q_1, q_2)$  of  $G$ 
19          $B.\text{DrawEdge}((q_1, q_2), \text{column})$ 
20         if  $q_1$  finished then
21             ActiveVertices.remove( $q_1$ )
22         if  $q_2$  finished then
23             ActiveVertices.remove( $q_2$ )
24     else if  $v$  is  $P$  node then
25         column  $\leftarrow \text{column} + 1$ 
26         for  $v \in \text{ActiveVertices}$  do
27              $B.\text{extendBox}(v)$ 
28              $l_{up} \leftarrow \text{layer}(p_1)$ 
29              $l_{low} \leftarrow \text{layer}(p_2)$ 
30     else if  $v$  is  $S$  node then ; // Serialization  $S(s_1, s_2, s_3)$ 
31         column  $\leftarrow \text{column} + 1$ 
32         for  $v \in \text{ActiveVertices}$  do
33              $B.\text{extendBox}(v)$ 
34             if  $\nexists$  free layer between layer( $s_1$ ) and layer( $s_3$ ) then
35                  $l \leftarrow B.\text{addLayer}(l_{up}, l_{low})$ 
36             else
37                  $l \leftarrow$  free layer between layer( $s_1$ ) and layer( $s_3$ )
38              $B.\text{DrawBox}(s_2, l)$ 
39             ActiveVertices.add( $s_2$ )
40     VerticesDone.add( $v$ )

```

---

The whole strategy is summed up in the following pseudocode:

---

**Algorithm 8:** DrawMaximalOuterplanar( $G'$ )

---

**Input:** Maximal Outerplanar Graph  $G'$

**Output:** Polyline drawing  $\Gamma_{G'}$  with two bends

- 1  $(T, W) \leftarrow$  tree decomposition of  $G'$  with lowest height
  - 2  $\mathcal{T}' \leftarrow f(T', W')$
  - 3  $\delta \leftarrow n$
  - 4  $\mathcal{B}_{G'} \leftarrow \text{DrawSPQR}(\mathcal{T}')$
  - 5  $\Gamma_{G'} \leftarrow \mathcal{B}_{G'}. \text{TransferToPolyline}$
  - 6 **return**  $\Gamma_{G'}$
- 

### 5.5.1 Analysis

Algorithm 8 takes a maximal outerplanar graph  $G'$  as input argument. Calculating the tree decomposition of  $G'$  with lowest height runs in  $\mathcal{O}(n)$  time since there are  $\mathcal{O}(n)$  faces in  $G'$ . Transferring the tree decomposition to an *SPQR*-Tree described by the function of Lemma 15 takes  $\mathcal{O}(|V(T')|) = \mathcal{O}(n)$  steps.

The drawing step described in Algorithm 7 takes the *SPQR*-Tree and creates a box drawing by iterating over its nodes. For the *SPQR*-Tree  $\mathcal{T}$ , there are  $\mathcal{O}(n)$   $P$ ,  $S$  and  $Q$  nodes, respectively. In case of a  $Q$  node, drawing an edge takes constant time. In case of either a  $P$  or a  $S$  node, there are  $\mathcal{O}(|\text{ActiveVertices}|)$  box extensions.

Transferring a box drawing to a polyline drawing includes the substitution of  $\mathcal{O}(n)$  boxes with a grid point and  $\mathcal{O}(n)$  edge reroutes over two bends per edge. The runtime therefore equals  $\mathcal{O}(n \cdot |\text{ActiveVertices}|)$ .

**Theorem 4.** *Let  $G'$  be a complete maximal outerplanar graph. The drawing algorithm 8 produces a polyline drawing  $\Gamma_{G'}$  on area  $\mathcal{O}(n'^2 \log n')$  with two bends per edge and ratio  $r \in \mathcal{O}(\log n')$ , when the minimal distance between two layers is set to  $n'$ .*

*Proof.* Consider the drawing algorithm 7, producing a box drawing  $\mathcal{B}_{G'}$ . The algorithm first creates a tree decomposition of  $G'$ ,  $(T', W')$ , and then uses DFS on  $T'$  in its iteration to explore new active vertices which will be drawn in a potentially new layer. An active vertex  $v$  blocks a layer of  $\mathcal{B}_{G'}$  for further vertex insertions. When the DFS finished exploring the subtree  $T'_v$  of  $T'$ , the layer of  $v$  is available for new vertex insertions.

Let  $p$  be a path from the root of  $T'$  to a leaf which creates the highest amount of layers. By Lemma 13, there are at most  $\mathcal{O}(\log n)$  vertices active during the DFS graph traversal of the tree decomposition of  $G'$ . Since  $T'_v$  is a chain of vertices for any vertex  $v \in V(G')$ , there exists a subtree of  $T'$  of asymptotically the same height as  $T'_v$  which does not contain  $v$  in its bags. After drawing  $\mathcal{O}(\log n)$  vertices defined by  $p$  on separate layers, the amount of layers created in  $\mathcal{B}_{G'}$  suffice for the remaining drawing and is asymptotically bound by  $\mathcal{O}(\log n)$ .

The resulting box drawing therefore inherits  $\mathcal{O}(\log n)$  layers with a pairwise distance of  $n$ . The height of the drawing is bound by  $\mathcal{O}(n \log n)$ . Since for every edge of  $G'$  there exists a column in  $\mathcal{B}_{G'}$ , the width is bound by  $\mathcal{O}(n)$ . The total area consumption therefore lies in  $\mathcal{O}(n^2 \log n)$ .

When transferring the box drawing  $\mathcal{B}_{G'}$  to a polyline drawing  $\Gamma_{G'}$ , every box



$b_v$  is substituted with a grid point  $v$  inside of  $b_v$  and every edge incident to  $b_v$  is rerouted by a bend point to the grid point for  $v$ . The polyline drawing produced by algorithm 8 inherits two bends per edge and has asymptotically the same area bound as the box drawing of algorithm 7. The longest edge  $l_{\max}$  spans the width and the height and its length is bound by  $\mathcal{O}(n \log n) + \mathcal{O}(n) = \mathcal{O}(n \log n)$ . The minimal Euclidian distance between adjacent vertices values  $n$  implied by the layering with its distance and the ratio therefore lies in  $\mathcal{O}(\log n)$ .  $\square$

**Theorem 5.** *Let  $G'$  be a maximal outerplanar graph. The drawing algorithm 8 produces a polyline drawing  $\Gamma_{G'}$  on area  $\mathcal{O}(n'^2 \log^2 n')$  with two bends per edge and ratio  $r \in \mathcal{O}(\log^2 n')$ , when the minimal distance between two layers is set to  $n'$ .*

*Proof.* Considering Lemma 14, up to  $\mathcal{O}(\log^2 n')$  are active simultaneously when traversing the tree decomposition of  $G'$  with DFS and prioritizing the subtrees of minimal height. Analogously to the proof of Theorem 4, there are up to  $\mathcal{O}(\log^2 n')$  layers inserted into the box drawing which will suffice for the whole drawing of  $G'$ . After transferring the box drawing to a polyline drawing, the resulting height lies in  $\mathcal{O}(n \log^2 n)$ . The width still lies in  $\mathcal{O}(n)$ . The ratio is therefore bound by  $\mathcal{O}(\log^2 n')$ .  $\square$

**Theorem 6.** *There exists a class of maximal outerplanar graphs for which every graph admits a polyline drawing on  $\mathcal{O}(n^2)$  area with a constant ratio.*

*Proof.* Let  $G'$  be a maximal outerplanar graph with its partitioning  $P = (\mathcal{P}, \mathcal{W})$ . Let  $c$  be a constant so that for every partition  $p_i \in \mathcal{P}$  it holds that  $|w_i| \leq c$ ,  $w_i \in \mathcal{W}$  and  $\mathcal{P}$  be a chain of vertices of height  $\mathcal{O}(n)$ . Since the size of every partition is bound by  $c$ , the height of the regarding complete  $k$ -ary tree is bound by  $\mathcal{O}(1)$ .

When  $\mathcal{P}$  is a chain of vertices, the drawing algorithm 8 finishes a partition before proceeding to the next element of  $\mathcal{P}$  due to the combined strategy of DFS and subtree priority. Since the amount of layers inserted into  $\mathcal{B}_{G'}$  are determined by the amount of simultaneously active vertices,  $\mathcal{B}$  inherits a constant amount of layers, resulting in a box drawing of  $\mathcal{O}(n^2)$  area and a constant ratio.  $\square$

## 5.5.2 Example Drawing

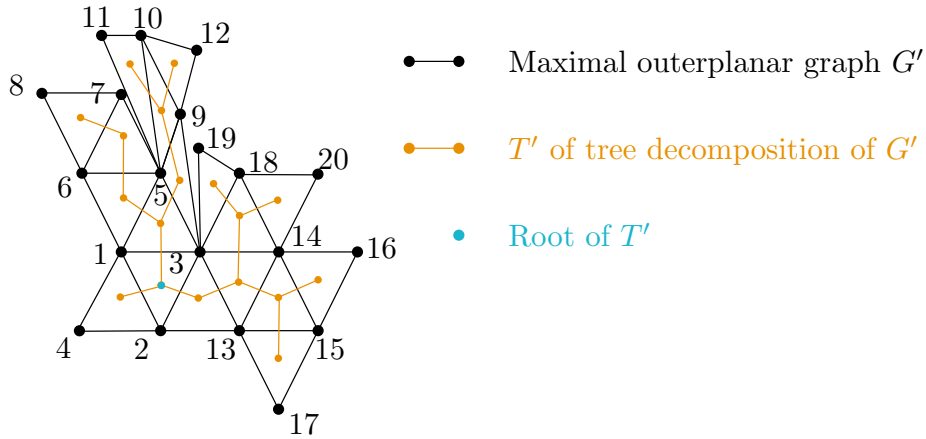
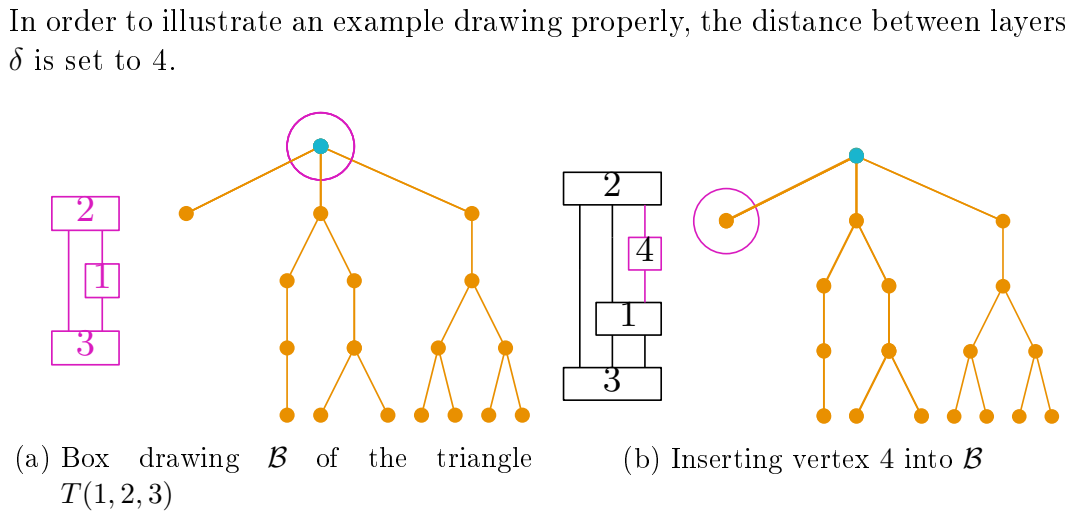


Figure 18: A straight-line drawing of a maximal outerplanar graph  $G'$  with  $T'$  out of its tree decomposition

The drawing algorithm draws the triangle defined vertices 1, 2 and 3 on three different layers and then explores  $T'$  by DFS and prioritizes the subtree of minimal height. In the illustration of  $T'$ , the magenta enclosure illustrates the progression of the DFS.



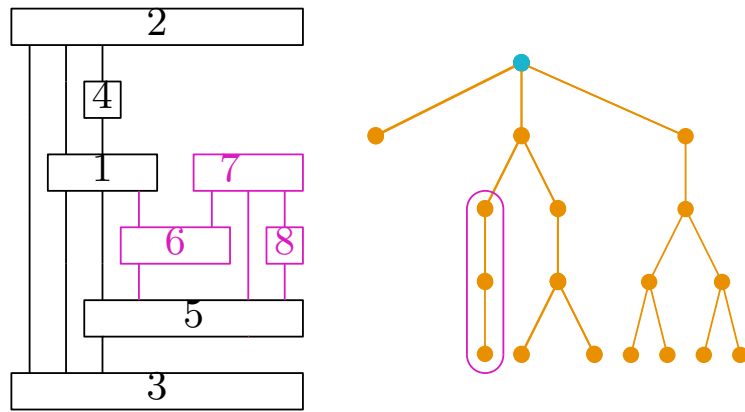


Figure 20: After drawing vertex 6, vertex 1 is finished and the vertices 6 to 8 alternate between two layers

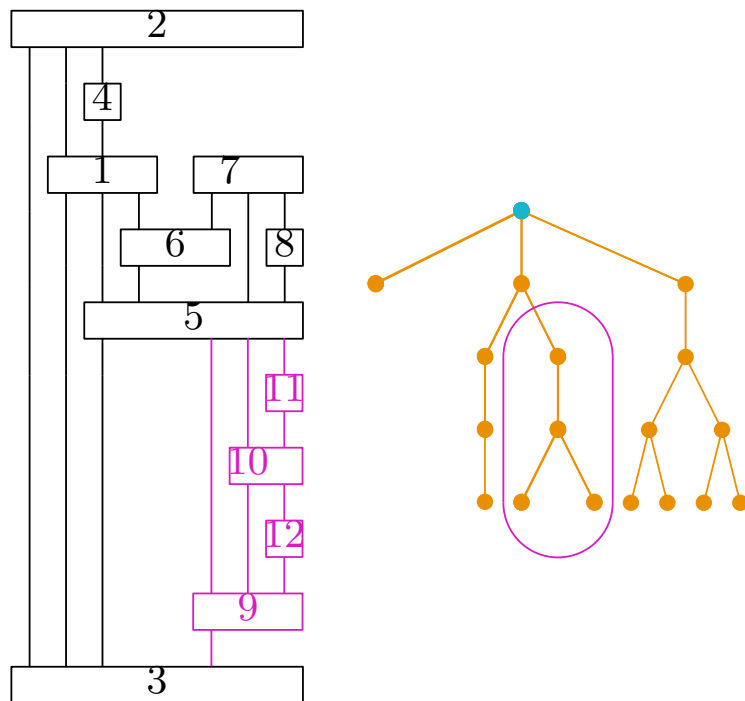


Figure 21: The subtree adjacent to vertices 5 and 3 is drawn

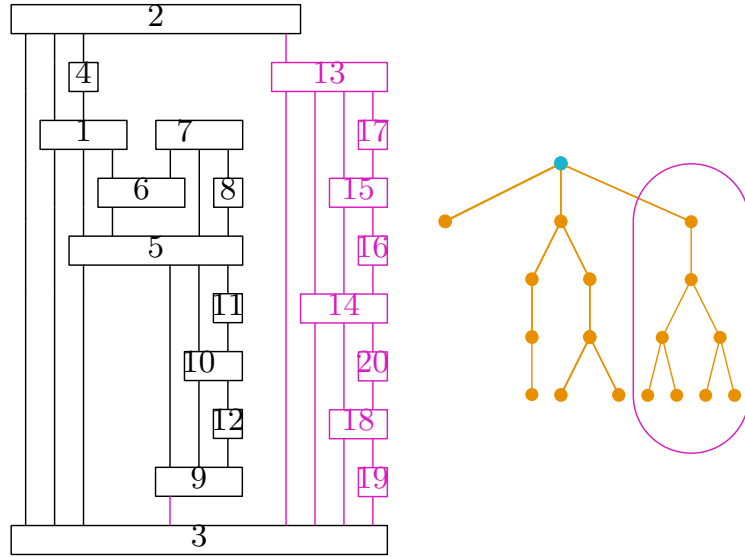
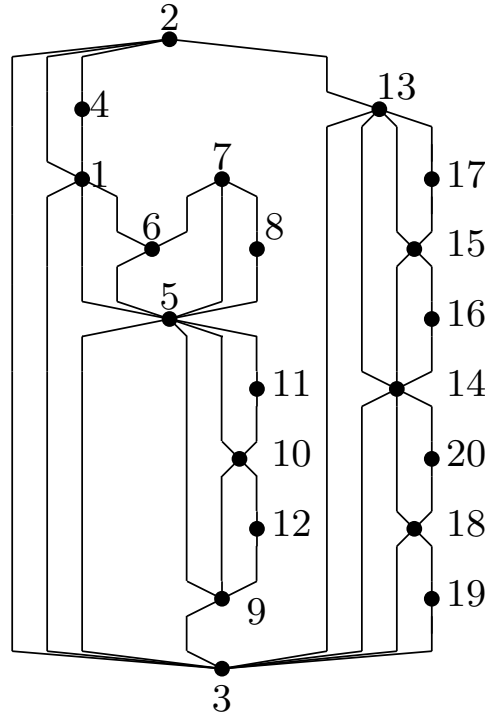


Figure 22: The subtree adjacent to vertices 2 and 3 is drawn

Figure 23: The resulting polyline drawing  $\Gamma_{G'}$  derived from  $\mathcal{B}_{G'}$ , with two bends per edge

### 5.5.3 Preserving Outerplanarity

**Theorem 7.** *There exists an alternation of Algorithm 7 that preserves the outerplanarity property of  $\mathcal{G}'$  in a resulting box drawing  $\mathcal{B}_{G'}$ .*

*Proof.* Start at the root of  $T'$ , drawing a triangle on three layers. Without loss of generality, let  $v_1$  be on the top layer,  $v_2$  on the bottom layer and  $v_3$  inbetween, placed left of the edge  $(v_1, v_2)$ . Since  $G'$  is maximal outerplanar, by Lemma 10 the three binary subtrees adjacent to the root of  $T'$  address either  $(v_1, v_2)$ ,  $(v_1, v_3)$  or  $(v_2, v_3)$ . If a binary subtree refers to  $(v_1, v_3)$ , draw to the left

inbetween the regarding layers. Analogously for the binary tree referring to  $(v_2, v_3)$ . If a binary subtree refers the edge  $(v_1, v_2)$ , draw to the right.

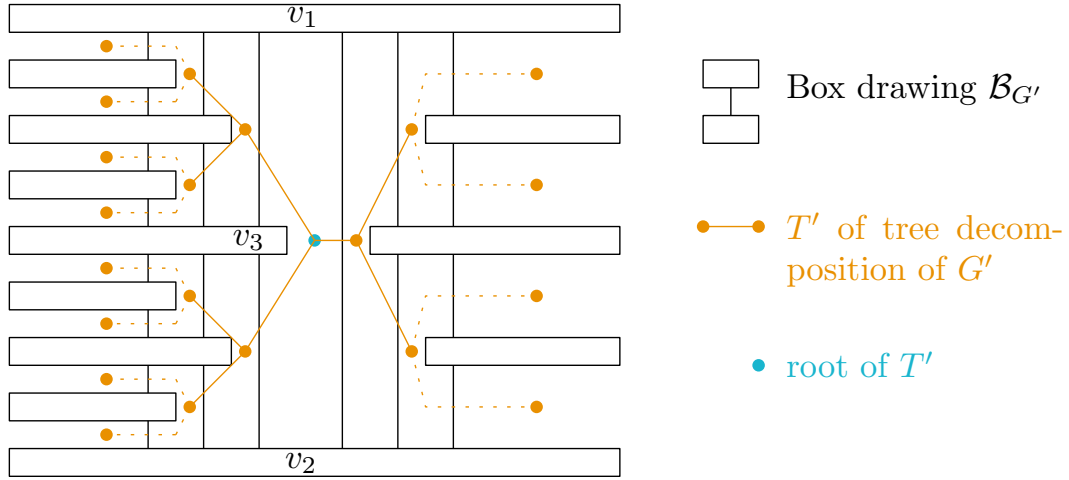


Figure 24: Scheme to draw a complete maximal outerplanar graph with preserving the outerplanarity property

Since every box of  $\mathcal{B}_{G'}$  lies on the outerface, every vertex lies on the outerface in the resulting polyline drawing  $\Gamma_{G'}$ . The runtime, area consumption and ratio do not alter asymptotically.  $\square$

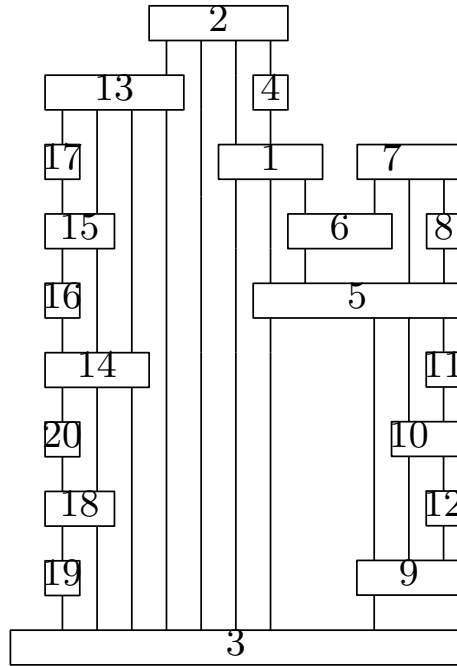


Figure 25: Alternate box drawing of example illustrated at 22, preserving outerplanarity

## 6 Maximal Series-Parallel Graphs

Maximal series-parallel graphs correspond to the class of 2-trees [1, P. 2] and are a suitable class of interest for fundamental research since any 2-tree is biconnected, but not triconnected and inherits a constant treewidth. Creating a compact layered polyline drawing for maximal outerplanar graphs will prove to be useful when drawing maximal SP-graphs. Every maximal SP-graph contains a maximal outerplanar subgraph.

### 6.1 Properties Of Maximal Series Parallel Graphs

**Lemma 16.** *There exists a linear time algorithm which computes the largest maximal outerplanar subgraph for any maximal SP-graph.*

*Proof.* Consider the tree decomposition  $(T, W)$  of  $G$ . Add the root of  $T$  to  $T'$  and its bag to  $W'$ . From the root of  $T$ , pick the three children which root the subtrees with the maximum height and size and their respective bags. Then, recursively pick the two children which root the subtrees with the maximum height and size and add them to  $T'$  with their respective bags to  $W'$ . This procedure terminates some leaves of  $T$ .

Every vertex of the resulting  $T'$  is of degree maximum 3 and by Lemma 8, the graph  $G'$  induced by  $T'$  is maximal outerplanar. Since during this procedure, the nodes with the maximum subtrees are chosen and the properties described in Lemma 10 hold, there exists no other maximal outerplanar subgraph of  $G$  which is larger.  $\square$

**Lemma 17.** *Let  $G$  be a maximal SP-graph with tree decomposition  $(T, W)$  and  $G'$  any maximal SP subgraph of  $G$  with tree decomposition  $(T', W')$ . Then, it holds:*

1.  $(T', W') \subseteq (T, W)$
2. *There exists a vertex in  $T \setminus T'$  whose bag shares exactly two vertices of  $G$  with the bag of the root of  $T'$*

*Proof.* • Since the tree decomposition of a maximal SP-graph is unique, any maximal SP subgraph  $G'$  of  $G$  is represented in  $T$  by  $T'$ .

- Let  $t$  be the root of  $T'$ . Consider the parent of  $t$  in  $T$ . This property holds between those bags by Lemma 9.

$\square$

### 6.2 Drawing Algorithm For Maximal Series Parallel Graphs With Two Bends

A maximal SP-graph  $G$  with its tree decomposition  $(T, W)$  will be evaluated for its largest maximal outerplanar subgraph  $G'$  with tree decomposition  $(T', W')$ .  $\tilde{T}$  describes the difference of  $T$  and  $T'$  and is a set of subtrees of  $T$ .

In order to create a polyline drawing similarly as described in section 5, it is crucial to find a suiting  $SPQR$  tree derivation of a maximal SP-graphs for the box drawing algorithm 7 to function. Fortunately, the function deriving a  $SPQR$  tree of a tree decomposition of a maximal outerplanar graph  $G'$  is also applicable for maximal SP-graphs.

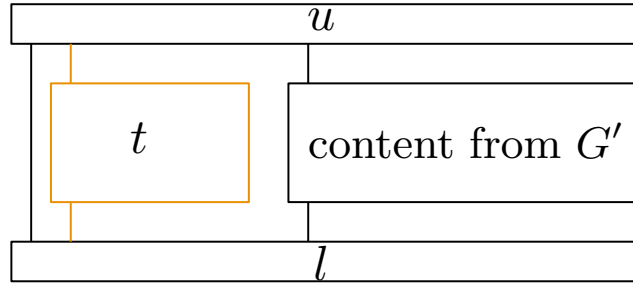
**Lemma 18.** *The function deriving a SPQR tree from a tree decomposition defined in Lemma 15 is applicable to any maximal SP-graph  $G$ .*

*Proof.* Let  $G$  be a maximal SP-graph with its tree decomposition  $(T, W)$ . Contrary to a tree decomposition of a maximal outerplanar graph, any node  $T$  can have arbitrary many children. Inserting a new vertex described with a vertex in  $T$  works analogously to the prior scheme. For a maximal SP-graph, the resulting SPQR tree can inherit arbitrary many serial nodes attached to a parallel node.  $\square$

After  $(T', W')$  is drawn into a box drawing  $B'$ , the remaining subtrees in  $\tilde{T}$  will be inserted accordingly, resulting in a box drawing  $B$  for  $G$ . Finally, a polyline drawing will be derived from  $B$ .

**Lemma 19.** *Let  $G$  be a maximal SP-graph and  $G'$  its largest maximal outerplanar graph with its box drawing  $\mathcal{B}_{G'}$  created by Algorithm 7. For every tree  $t$  in  $\tilde{t}$  there exists a column in  $\mathcal{B}_{G'}$  where  $t$  can be inserted into without destroying planarity.*

*Proof.* Consider the two shared vertices  $u, l \in G$  of the root of  $t$  with its parent. Since the parent of  $t$  is part of  $G'$ ,  $u$  and  $l$  are placed on their respective layers in  $\mathcal{B}_{G'}$  and connected by an edge at column  $x$  with its content drawn from  $G'$ . Insert  $t$  by slicing the box drawing so that there are sufficient free columns beginning at  $x + 1$  and draw  $t$ . This way, planarity is preserved.



(a)  $t$  inserted inbetween upper and lower layer  $u$  and  $l$  (colored in orange)

$\square$

---

**Algorithm 8:** DrawMaximalSPGraph( $G$ )

---

**Input:** Maximal Series Parallel Graph  $G$

**Output:** Polyline Drawing  $\Gamma_G$  with two bends per edge

```

1  $(T, W) \leftarrow$  tree decomposition of  $G$ 
2  $G' \leftarrow$  largest maximal outerplanar subgraph of  $G$ 
3  $(T', W') \leftarrow$  tree decomposition of  $G'$ 
4  $\tilde{T} \leftarrow T \setminus T'$ 
5  $\Gamma_{G'} \leftarrow$  DrawMaximalOuterplanar( $G'$ )
6 for  $t \in \tilde{T}$  do
7    $p \leftarrow \text{parent}(t.\text{root})$ 
8    $u \leftarrow \Gamma_{G'}.upperLayer(p)$ 
9    $l \leftarrow \Gamma_{G'}.lowerLayer(p)$ 
10   $\Gamma_{G'}.Insert(t, u, l)$ 
11 return  $\Gamma_{G'}$ 

```

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### 6.2.1 Analysis

**Lemma 20.** *When the remaining subtrees of  $\tilde{t}$  are inserted into a box drawing  $\mathcal{B}_{G'}$ , the area bounds do not increase asymptotically.*

*Proof.* Let  $G$  be a maximal SP-graph with  $\mathcal{B}_{G'}$  a box drawing from the largest maximal outerplanar graph of  $G$  created by Algorithm 7. For the insertion of  $t \in \tilde{t}$  into  $\mathcal{B}_{G'}$ , consider the subtrees adjacent to the parent  $p$  of  $t$  in  $T$ . Since  $t$  is not in  $T'$ , there exists subtree  $t'$  of  $T'$  adjacent to  $p$  which was already drawn.

If the insertion of a tree  $t$  would create more layers than drawing  $t'$  in the first place resulting in a new upper bound for the height of the drawing, then there would be a maximal outerplanar subgraph of  $G$  containing  $t'$  which is contradicting the assumption. In the width of the drawing, there are still as many columns as there are edges in  $G$ . The area bounds do not increase asymptotically.  $\square$

**Theorem 8.** *Any maximal SP-graph admits a polyline drawing in  $\mathcal{O}(n^2 \log^2 n)$  area with two bends per edge and a ratio bound by  $\mathcal{O}(\log^2 n)$ , when the minimal distance between two layers is set to  $n$ .*

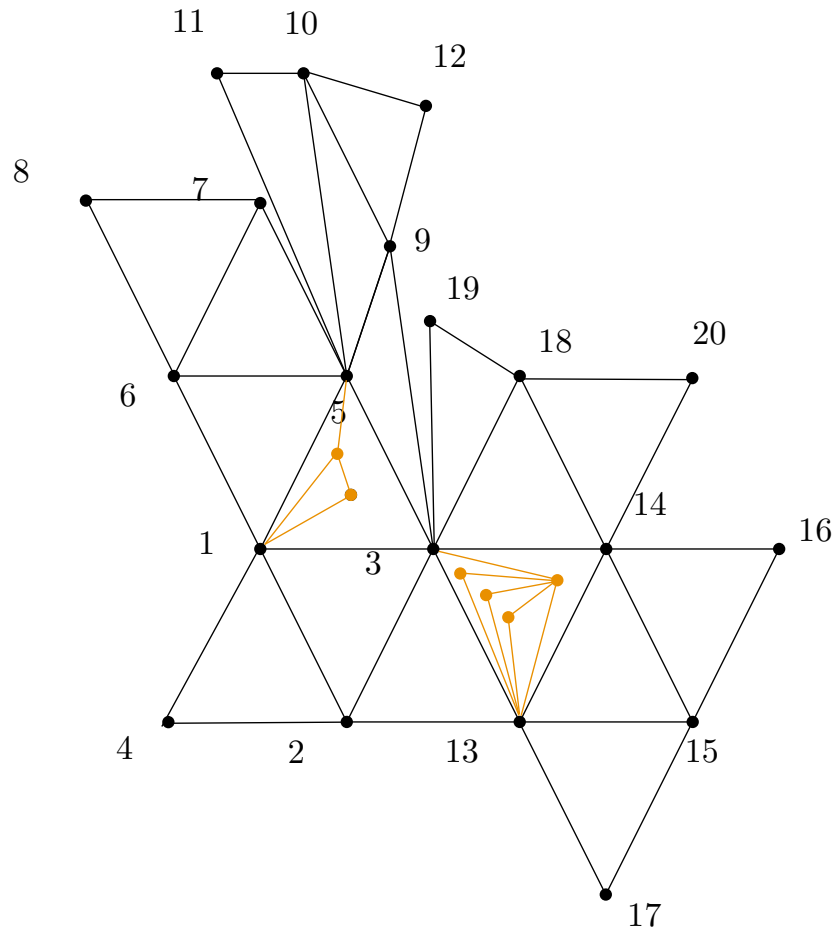
*Proof.* Let  $\mathcal{B}_{G'}$  be the box drawing of the largest maximal outerplanar subgraph  $G'$  of a maximal SP-graph  $G$ . The width of  $\mathcal{B}_{G'}$  lies in  $\mathcal{O}(n')$ . Inserting the remaining subtrees of  $\tilde{t}$  increases the width asymptotically to  $\mathcal{O}(n)$  since there is at most one column per edge of  $G$ . Lemma 20 states that the height bound is asymptotically not altered and analogously to the proof of theorem 5, the ratio of the resulting polyline drawing  $\Gamma_G$  is bound by the amount of total layers, when the minimal distance is set to  $n$ .  $\square$

**Theorem 9.** *Any maximal SP-graph admits a polyline drawing in  $\mathcal{O}(n \log^2 n)$  area with two bends per edge.*

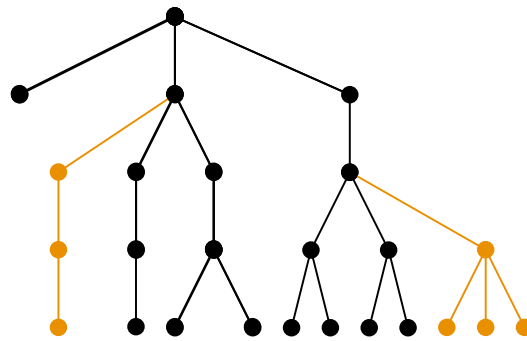
*Proof.* When the minimal distance between two layers is set to a constant, the resulting height is bound by the amount of simultaneously active vertices. The resulting drawing  $\square$



### 6.3 Example drawing



(a) Maximal SP-graph  $G$  with its largest maximal outerplanar subgraph from example 18. The differential subtrees are colored in orange



(b)  $T$  of the tree decomposition of  $G$

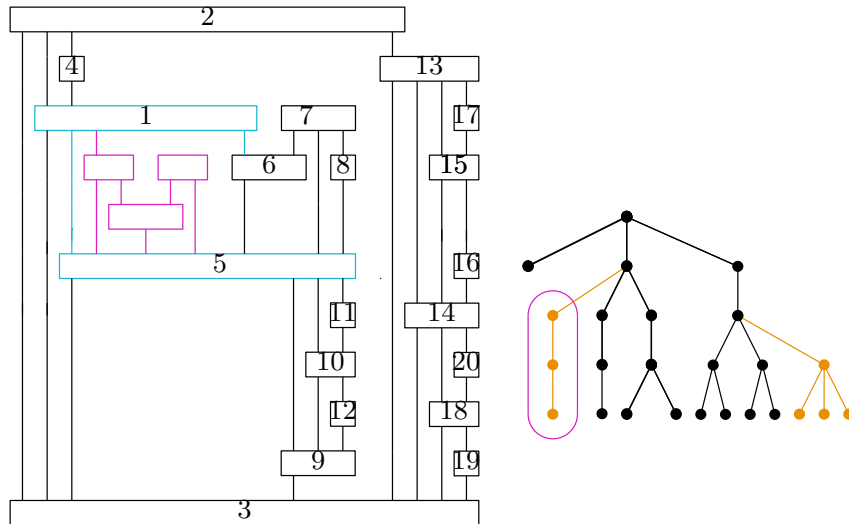


Figure 28: The first differential subtree (encircled in magenta) is inserted between vertices 1 and 5 right next to the edge of (1,5) (colored in cyan). Since 1 is not finished during the insertion, creating a new layer is mandatory

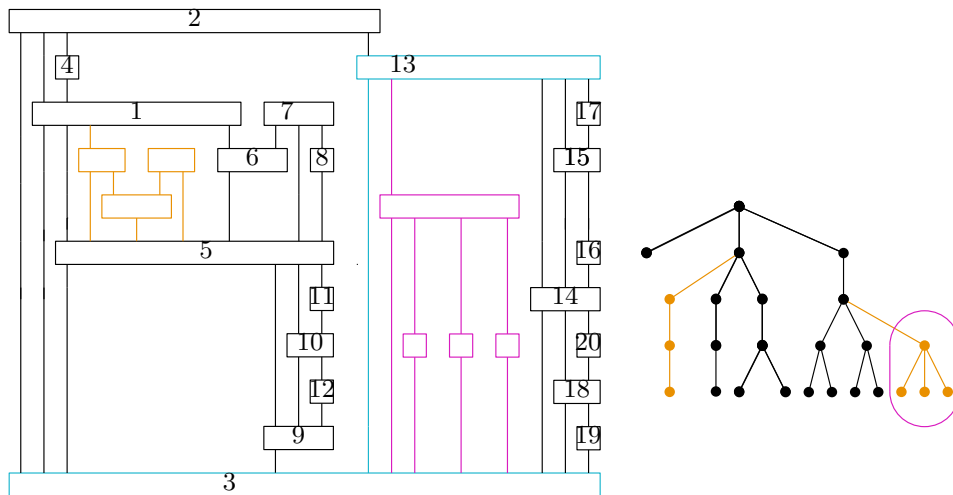


Figure 29: The second differential subtree (encircled in magenta) is inserted between vertices 13 and 3 right next to the edge of (13,3) (colored in cyan)

## 7 Related Work

### 7.1 3-trees

Following the recursive definition of  $k$ -trees, 3-trees start with a  $K_4$  and every new added vertex is connected to three adjacent vertices. 3-trees inherit a treewidth of 3 and  $R$  nodes in the respective  $SPQR$  tree since they are triconnected. The box drawing algorithm 7 does not suffice for this class of planar graphs since the algorithm does not handle the  $R$  node case. Still, it is of interest how the idea of a layered box drawing approach will work out based on the tree decomposition of a 3-tree.

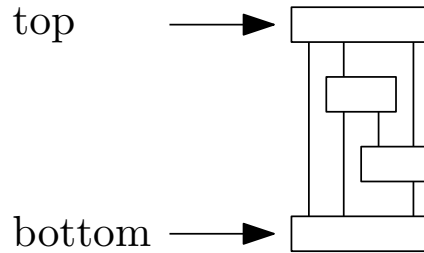
**Definition 4.** Let  $G$  be a 3-tree with its tree decomposition  $(T, W)$ .  $G$  is called complete, if the following property holds:

- Every vertex of  $T$  is either a leaf or of degree 4
- The leaves of  $T$  have uniform heights

In other words,  $G$  is called complete if the root of  $T$  is the parent of 4 complete tertiary trees of the same height.

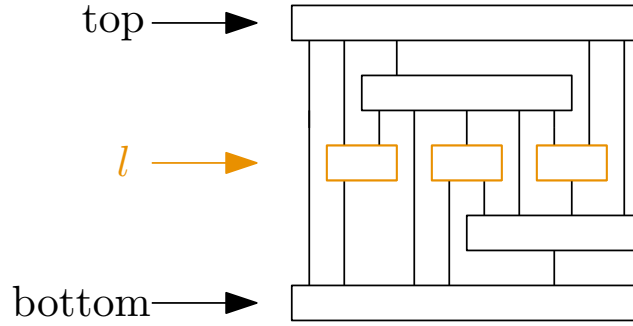
**Observation 2.** Let  $G$  be a complete 3-tree. Applying a layering scheme similar to algorithm 6, the resulting box drawing  $\mathcal{B}_G$  is at least in area bound  $\mathcal{O}(n^2)$ , when the minimal distance between layers is set to a constant.

In order to validate this observation, a box drawing of  $K_4$  is created as illustrated.  $K_4$  represents the root of the tree decomposition of a complete 3-tree  $G$  with height 0 in its tree decomposition  $T$ . Let  $\mathcal{L}_0$  be the list of layers consisting of the topmost and bottommost layer of the  $K_4$  for  $h = 0$ .



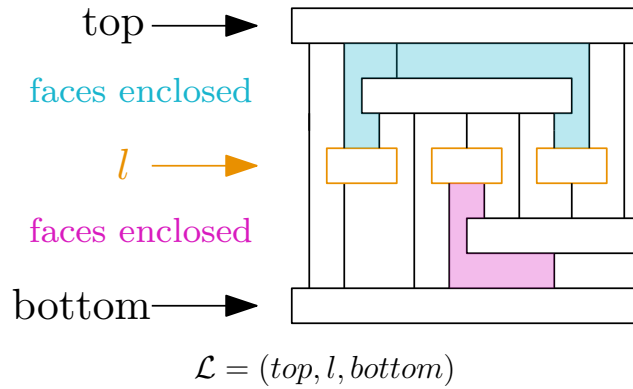
$K_4$  drawn on four different layers.  $\mathcal{L}_0 = (top, bottom)$

The amount of layers created while inserting vertices will determine the height of the resulting drawing. A complete 3-tree  $G$  with height  $h$  in  $T$  is extended to a complete 3-tree  $G^+$  with height  $h + 1$  when for every inner face  $f$  a vertex is inserted and connected to the vertices defining  $f$ . These newly created layers are inserted into  $\mathcal{L}_h$  according to their position from top to bottom, resulting in  $\mathcal{L}_{h+1}$ .



One layer insertion in  $\mathcal{B}$  when extending the height of  $T$  from 0 to 1.

Let  $l$  be the layer where the new vertices are inserted in according to this scheme. Every vertex insertion creates three new faces out of a pre-existing one. Unfortunately, for any layer  $l$ , there will be a face encapsulated between  $l$  and both its predecessor and successor in  $\mathcal{L}$ .



So, in order to insert vertices in all the inner faces so that  $G$  is a complete 3-tree and the height of  $T$  will be incremented by 1, there are  $|\mathcal{L}_h| - 1$  at least new layers necessary.

For a complete 3-tree with height  $h$  in its tree decomposition, the total amount of layer insertions is calculated the following way:

$$\sum_{i=0}^h 2^i = 2^{h+1} - 1 \quad \underbrace{\in}_{h \in \mathcal{O}(\log n)} \mathcal{O}(n)$$

The resulting box drawing will therefore consume at least  $\mathcal{O}(n^2)$  area, when the minimal distance between two layers values a constant. In conclusion, no ratio optimization is possible with this layering approach.

## 8 Future Work

### Tightness Of Ratio Upper Bound For Maximal SP Graphs

As shown in section 5, the amount of simultaneously active vertices during a DFS graph traversal through a maximal outerplanar graphs tree decomposition lies in  $\mathcal{O}(\log^2 n)$ . One question is whether this upper bound is sharp. It might be possible to deduce the amount of active vertices of  $G$  for a path from the root of the tree decomposition to any leaf. The consequence would be a significantly smaller area bound and ratio of any polyline drawing.

### Polyline Drawing Implementation For Maximal SP Graphs

An implementation of the drawing algorithm 8 would help evaluating the readability, aesthetics and the ratio of polyline drawings for large-scale maximal SP graphs. In order to implement the algorithm, it is necessary to guarantee consistent data structure representations regarding *undirected graphs* and *SPQR trees* in a programming language of choice. Then, implementing the pseudocodes described in section 5 and 6 would be straight-forward.

### Drawing Approach For 3-trees

Since in section 7 it was illustrated that the layering approach based on a tree decomposition is not suitable for a ratio optimization for the class of 3-trees, a new approach for a polyline drawing algorithm is desirable.

### General Drawing Algorithm For $k$ -ary Trees

The drawing algorithm 1 considers a  $k$ -ary tree to be complete in order to produce a straight-line drawing. While any  $k$ -ary tree admits a straight-line drawing with nearly-optimal ratio, the area consumption might behave exponentially if the  $k$ -ary tree is of height  $\mathcal{O}(n)$ . It would be desirable to construct a drawing algorithm for any input  $k$ -ary tree so that the area consumption of the resulting drawing stays reasonable and compact while not increasing the nearly-optimal ratio.

## 9 Acknowledgements

I would like to thank Prof. Dr. Michael Kaufmann for instructing this final thesis. Further I appreciate helpful discussions with Dr. Henry Förster, Julia Katheder and Axel Kuckuk, you guys will shape the teaching in university well for the greater good. I want to thank my parents for encouraging me to absolve the Masters' degree course of computer science.

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