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A Simple Near Optimal Parallel Algorithm for Recognizing Outerplanar Graphs

Shin-ichi Nakayama (中山 慎一) Shigeru Masuyama (増山 繁)

Department of Knowledge-Based Information Engineering,
Toyohashi University of Technology
Toyohashi-shi, Aichi 441, Japan
E-mail: shin@toki.tutkie.tut.ac.jp, masuyama@tutkie.tut.ac.jp

Abstract. An outerplanar graph is a graph which can be embedded in the plane so that all vertices lie on the boundary of the exterior face. In this paper, we propose a simple near optimal parallel algorithm for recognizing whether a given graph G is outerplanar in $O(\log n)$ time using $O(n\alpha(l,n)/\log n)$ processors on an arbitrary-CRCW PRAM where n is the number of vertices in G, $\alpha(l,n)$ is the inverse Ackermann function, which grows extremely slowly with respect to l and n[9] and $l = O(n)$. Although a near optimal parallel algorithm for general graphs can also be obtained by combining the algorithm in [3] with the algorithm for finding biconnected components[4][9], our algorithm uses methods completely different from the algorithm in [3]'s and is much simpler than [3]'s.

1 Introduction

An outerplanar graph is an undirected graph which can be embedded in the plane in such a way that all vertices lie on the exterior face(, see Fig. 1). A graph always denotes an undirected graph throughout this paper, except when it is specified to be directed. For outerplanar graphs, several efficient algorithms for solving important problems e.g., vertex-coloring, edge-coloring, longest path, are known [9][5]. Furthermore, it is well-known that a given graph is outerplanar if and only if a given graph has page number one, where graph G has page number one if there exists a linear arrangement of vertices so that no pair of edges is crossing when they are drawn on the same side of the linear arrangement of the vertices [13][11]. The problem of deciding whether a given graph has page number one is the special case of the book embedding, whose application to fault-tolerant VLSI design is described e.g., in the introduction of [13]. Thus, it is useful to develop efficient algorithms for recognizing whether a given graph is outerplanar or not.

Mitchell [10] proposed an $O(n)$ sequential algorithm for recognizing outerplanar graphs where n is the number of vertices in G. The sequential algorithm removes a vertex v satisfying some properties from a given graph G step by step, and cannot straightforwardly be applied to develop an efficient parallel algorithm. Diks, Hagerup and Rytter [3] developed a parallel algorithm for recognizing outerplanar graphs. When an input graph is biconnected, the algorithm [3] runs in $O(\log n)$

time using $O(n/\log n)$ processors on a CRCW PRAM (, see e.g., [8]), where n is the number of vertices in G. However, when an input graph is a general graph, we need to find biconnected components before applying the algorithm [3] to each biconnected component. The best known parallel algorithm for finding biconnected components runs in $O(\log n)$ time using $O((n+m)\alpha(m,n)/\log n)$ processors on the arbitrary-CRCW PRAM [4] [9] where m is the number of edges and $\alpha(m,n)$ is the inverse Ackermann function, which grows extremely slowly with respect to m and n [9]. † The arbitrary-CRCW PRAM is defined by the property that when several processors try to write to the same memory cell in the same step, then exactly one of them succeeds [8]. As outerplanar graphs have at most $2n-3$ edges [10], by checking this fact first, we can find biconnected components in $O(\log n)$ time using $O(n\alpha(l,n)/\log n)$ processors on the arbitrary-CRCW PRAM where $l = O(n)$. Thus, the algorithm [3] combined with the algorithm for finding biconnected components [4] [9] takes, in total, $O(\log n)$ time using $O(n\alpha(l,n)/\log n)$ processors on the arbitrary-CRCW PRAM, when applied to general graphs. Similarly, on a CREW PRAM(, see e.g., [8]), the complexity of parallel algorithm [3] is dominated by finding biconnected components, when applied to general graphs.

In this paper, we present a simple near optimal parallel algorithm for recognizing outerplanar graphs in $O(\log n)$ time using $O(n\alpha(l,n)/\log n)$ processors on the arbitrary-CRCW PRAM, in the sense that $O(\log n) \times O(n\alpha(l,n)/\log n) = O(n\alpha(l,n))$ is almost linear with respect to n. Although a near optimal parallel algorithm for general graphs can also be obtained by combining the algorithm in [3] with the algorithm in [4] [9], our algorithm uses methods completely different from the algorithm in [3]'s, e.g., the well known st-numbering, and is much simpler than [3]'s.

†If the class of input graphs is *linearly contractible graph class* [7] such as the class of planar graphs, an optimal parallel algorithm for finding biconnected components that runs in $O(\log n)$ time using $O(n/\log n)$ processors on the arbitrary-CRCW PRAM exists [7]. However, this algorithm does not work for general graphs.

2 Definitions

Given an undirected connected graph $G = (V, E)$ having no multiple edges. A path P from v_0 to v_k in G is a finite non-null sequence $v_0, e_1, v_1, e_2, v_2, \cdots, e_k, v_k$, $v_i \in V$, $i = 0, 1, \cdots, k$, $e_j \in E$, $j = 1, 2, \cdots, k$, such that, for $1 \le i \le k$, the end vertices of e_i are v_{i-1} and v_i, respectively. If $v_0 = v_k$, then path P is a circuit.

A biconnected graph G is a connected graph which has no vertex v such that $G - v$ (the graph obtained by removing v from G) has at least two connected components. A biconnected outerplanar graph has a planar embedding consisting of a circuit bounding the exterior face, where (possibly) a number of non-crossing edges are embedded within the interior region of this circuit [5]. Edges on the boundary of the exterior face are called *sides*, while the other edges are called *diagonals* [5].

Next, we describe the *st-numbering* used in our parallel algorithm.

Definition 1 [12] An st-numbering is a one-to-one function f from V to $\{1, \cdots, n\}$ satisfying the following two conditions :

(i) $f(s) = 1$ and $f(t) = n$,

(ii) for each $v \in V - \{s,t\}$, there exist adjacent vertices v_1 and v_2 such that $f(v_1) < f(v) < f(v_2)$.

Fig. 2 illustrates st-numbering. The st-numbering is used as an indispensable component in several algorithms [12]. We have the following theorem.

Theorem 1 *[12] A graph G is biconnected if and only if it has an st-numbering by letting $s = u$ and $t = v$ for each edge (u,v).*

(Note 2.1) If graph G is biconnected, its st-numbering can be obtained in $O(\log n)$ time using $O((n+m)\alpha(m,n)/\log n)$ processors [4] where n (resp., m) is the number of vertices (resp., edges) in G and $\alpha(m,n)$ is the inverse Ackermann function.

3 The Parallel Algorithm

We first assume that the given graph G is biconnected. We shall describe how to treat general graphs at the end of this section. The following theorems characterize outerplanar graphs.

Theorem 2 *[6] Given graph $G = (V,E)$, G is outerplanar if and only if G has no subgraph homeomorphic to either K_4 or $K_{2,3}$, where K_4 is the complete graph on four vertices and $K_{2,3}$ is the graph illustrated in Fig. 3.* □

Theorem 3 *[10] An outerplanar graph G with $n(\geq 3)$ vertices has*

(i) at most $2n-3$ edges,

(ii) at least two vertices of degree 2. □

Our parallel algorithm first checks, based on Theorem 3, if G has at most $2n-3$ edges and at least two vertices of degree 2. Then, this algorithm chooses a vertex v of degree 2 and a vertex v' incident to v; regards v (resp., v') as s (resp., t) and finds st-numbering of G. Note that, by Note 2.1 just after Theorem 1, we can find st-numbering of G because G is assumed to be biconnected. When G is outerplanar, exactly one Hamiltonian circuit always exists in G, and the edges constructing the Hamiltonian circuit can be regarded as sides of the outerplanar graph [2][5]. Consequently, the above process finds the sides by the following lemma. In the following, suppose that the vertices in G are numbered from 1 to n by st-numbering where s is a vertex of degree 2 and t is a vertex incident to s and each vertex in G is identified with its vertex number.

Lemma 1 *If G is outerplanar, then all edges $(i, i+1)$, $i = 1, \cdots, n-1$, are in G.*

(proof) We shall show that, if G does not have some edge among $(i, i+1)$, $i = 1, \cdots, n-1$, then G is not outerplanar. Assume that vertex i is not incident to vertex i+1. By the definition of st-numbering, each vertex x, $x = 2, \cdots, n-1$, must be incident to a vertex whose number is less than x and to a vertex whose number is more than x, respectively. By this fact and the connectivity of G, G has simple path $P_{i,s} = i, j_1, j_2, \cdots, j_l, s$, $(l \geq 1)$ where $i > j_1 > j_2 > \cdots > j_l > 1(=s)$. Vertex 1 (=s) is adjacent to exactly two vertices n $(=t)$ and 2 by definition, so j_l of $P_{i,s}$ must be 2(, see Fig. 4). Similarly, for i+1, simple path $P_{i+1,s} = i+1, j'_1, j'_2, \cdots, j'_{l'}, s$, $(l' \geq 1)$ where $i+1 > j'_1 > j'_2 > \cdots > 2(= j'_{l'}) > 1(= s)$ exists.

Moreover, by the fact that each vertex x, $x = 2, \cdots, n-1$, must be incident to the vertex whose number is more than x, G has simple paths $P_{i,t} = i, k_1, k_2, \cdots, t$, where $i < k_1 < k_2 < \cdots < t(= n)$, and $P_{i+1,t} = i+1, k'_1, k'_2, \cdots, t$, where $i+1 < k'_1 < k'_2 < \cdots < t(= n)$.

Since $t > \cdots > k_2 > k_1 > i > j_1 > j_2 > \cdots > j_l > 1(= s)$, $P_{i,t}$ and $P_{i,s}$ share no vertex except i. Similarly, $P_{i,t}$ and $P_{i+1,s}$, $P_{i+1,t}$ and $P_{i,s}$, $P_{i+1,t}$ and $P_{i+1,s}$ share no vertex except i, $i+1$. G^*, constructed by $P_{i,s}, P_{i+1,s}, P_{i,t}$ and $P_{i+1,t}$, has a subgraph homeomorphic to $K_{2,3}$ (, see Fig 4). Hence, G is not outerplanar by Theorem 2, which however contradicts the assumption that G is outerplanar. Thus we have shown that if G is outerplanar, then G has all edges $(i, i+1)$, $i = 1, \cdots, n-1$. □

By Lemma 1, if at least one edge among $(i, i+1)$, $i = 1, \cdots, n-1$, does not exist in G, then the algorithm stops since G is not outerplanar, otherwise the edges $(i, i+1)$, $i = 1, \cdots, n-1$, and $(n, 1)$ construct a Hamiltonian circuit C. We regard the edges constructing C as sides of the outerplanar graph. (Note that if G is outerplanar, Hamiltonian circuit C is unique [5].)

We assume that C is embedded in the plane so that each edge of C bound the exterior face and the edges of $G - C$ ($G - C$ denotes the graph obtained by removing edges of C from G) are embedded within the interior region of C. The edges of $G - C$ are called *diagonals* of G. If the diagonals do not intersect each other on such embedded edges, then G is outerplanar, otherwise G is not outerplanar.

To see this, we execute the following process. Hereafter, we identify each vertex with its vertex number assigned by *st*-numbering.

Let $M(i)$, $i = 1, \cdots, n$, be an array such that $M(i)$ contains vertex j_0 where $j_0 \equiv \min\{ j \mid j$ is the endpoint of diagonals adjacent to i $\}$. If there is no diagonal incident to i, $M(i)$ has a value $+\infty$ where $+\infty$ is a sufficiently large number satisfying $+\infty > n$. For each diagonal (x, y) such that $x < y$, we execute $val(x, y) \leftarrow \min\{ M(i) \mid x \leq i \leq y \}$ and regard $val(x, y)$ as the value of diagonal (x, y). On the value $val(x, y)$ for each diagonal (x, y), we obtain the following lemma.

Lemma 2 *Assume that Hamiltonian circuit C is embedded in the plane so that each edge of C bounds the exterior face and diagonals are embedded within the interior region of C.*

The diagonals intersect each other if and only if there is a diagonal (x, y), where $x < y$, such that the value $val(x, y)$ is less than vertex number x.

(proof) ($\Rightarrow$) Assume that there is a pair of diagonals which intersect each other. Let (x, y), (x', y'), where $x < y$, $x' < y'$ and $x' < x$, be a pair of intersecting diagonals. As these two diagonals intersect each other, vertex y' satisfies $x < y' < y$ and is adjacent to diagonal (x', y') where $x' < x$ (See Fig. 6(a)). Hence, $val(x, y) = \min\{ M(i) \mid x \leq i \leq y \} < x$.

($\Leftarrow$) Assume that no diagonals intersect each other. Since no diagonals intersect each other, each vertex j adjacent to vertex i, where $x \leq i \leq y$, satisfies $x \leq j \leq y$ for each diagonal (x, y) where $x < y$ (See Fig. 6(b)). Hence, $val(x, y) = \min\{ M(i) \mid x \leq i \leq y \} \geq x$. □

In the following, we introduce **Procedure Recognition** for recognizing whether a given graph is outerplanar.

Procedure Recognition

begin

(Step 1) **if** $m > 2n-3$,
then print "G is not outerplanar" and stop.

(Step 2) **if** G does not have at least two vertices of degree 2,
then print "G is not outerplanar" and stop.

(Step 3) Choose a vertex v of degree 2 and a vertex v' incident to v; regard v and v' as s and t, respectively, and find an st-numbering of G [12][4].

(Step 4) **if** G does not have at least one edge among $(i, i+1)$ for all i, $1 \leq i \leq n-1$, where $i, i+1$ are the vertex numbers assigned by Step 3,
then print "G is not outerplanar" and stop.

(Step 5) For each vertex i, $i = 1, \cdots, n$,
$M(i) \leftarrow \min\{\ j \mid j$ is the endpoint of diagonals adjacent to $i\ \}$.

(Step 6) For each diagonal $e_j = (x, y)$ where $x < y$,
$val(x, y) \leftarrow \min\{\ M(i) \mid x \leq i \leq y\ \}$

(Step 7) **if** there is a diagonal (x, y), where $x < y$, such that $val(x, y) < x$,
then print "G is not outerplanar",
else print "G is outerplanar".

end. □

The correctness of Procedure Recognition is obvious by Theorem 3 and Lemmas 1 and 2. We then analyze the computation time and the number of processors required.

The complexity analysis is done under the assumption that each vertex of the input graph G has a pointer to its predefined adjacency list, that is, for each vertex $v \in V$, the vertices adjacent to vertex v are given in a liked list, say, $L[v] = \langle u_1,\ u_2,\ \cdots,\ u_d \rangle$, in some order, where d is the degree of v (Fig. 5(a)). Recall that the arbitrary-CRCW PRAM is used as a parallel computation model in this paper.

The list ranking algorithm [8] can handle steps 1, 2 in $O(\log n)$ time using $O(n/\log n)$ processors.

Note that $m = O(n)$ in the following analysis, as steps 3-7 are executed only when $m \leq 2n-3$ by step 1.

The parallel algorithm for finding st-numbering runs in $O(\log n)$ time using $O((n+m)\alpha(m,n)/\log n)$ processors [4] where n (resp., m) is the number of vertices (resp., edges) in input graphs and $\alpha(m, n)$ is the inverse Ackermann function. Thus, in step 3, finding st-numbering of G requires $O(\log n)$ time using $O(n\alpha(l, n)/\log n)$ processors where $l = O(n)$.

After finding the st-numbering, each of the initial vertex numbers in the adjacency lists $L[i]$'s is replaced by its number assigned by the st-numbering. For this process, we first transform the adjacency lists $L[i]$'s into a linked list L' as follows. Let a vertex u_d^i be the last element in the adjacency list $L[i]$ of vertex i and a vertex u_1^{i+1} the first element in $L[i+1]$. Each vertex u_d^i has a pointer to u_1^{i+1}, for $i = 1,\ \cdots,\ n-1$, (See Fig. 5(b)). We then convert the linked list L' into an array A by applying the list ranking algorithm [8] which runs in $O(\log n)$ time using $O(n/\log n)$ processors. And we replace each of the initial vertex numbers by its number assigned by st-numbering using a standard technique used to implement Brent's scheduling principle[5][8] as follows. Partition elements of A into equal-sized blocks E_i, $i = 1, \cdots, |A|/\log n$, where each size is $O(\log n)$. Treat each block E_i separately, and sequentially replace each of the initial vertex numbers belonging to block E_i by its number assigned by st-numbering. This process runs in $O(\log n)$ time using $O(n/\log n)$ processors.

Step 4 runs in $O(\log n)$ time using $O(n/\log n)$ processors by applying Brent's scheduling principle[5][8] stated in step 3.

Let $A[k, k']$, $1 \leq k < k' \leq |A|(= O(n))$ be an interval between k and k' in A. Note that the elements in A are numbers assigned by *st*-numbering. As the degree of each vertex is found in step 2, we can recognize the vertices adjacent to vertex v as the element in interval $A[k, k']$ where $1 \leq k < k' \leq |A|$. For example, assume that d_i is the degree of vertex i, the vertices adjacent to vertex 1 are the elements in $A[1, d_1]$, the vertices adjacent to vertex 2 are the elements in $A[d_1 + 1, d_1 + d_2]$, and so on. (Note: Given the degree of each vertex, the intervals in A corresponding to vertex i for $i = 1, \cdots, n$, are found in $O(\log n)$ time using $O(n/\log n)$ processors by applying prefix-sums algorithm [8].) Hence, in step 5, finding each minimum vertex number adjacent to vertex i for $i = 1, \cdots, n$, can be done by computing the minimum of interval in A corresponding to vertex i. As described in [8](pp. 131-136), after executing a preprocessing algorithm (ALGORITHM 3.8 in [8]) which runs in $O(\log n)$ time using $O(n/\log n)$ processors, we can compute the minimum $A_{min}[k_i, k_i']$ of $A[k_i, k_i']$, that is, $\min\{A(k_i),\ A(k_i + 1),\ \cdots,\ A(k_i')\}$, where $1 \leq k_i < k_i' \leq |A|$, in $O(1)$ time using $O(1)$ processors. We need to compute the minimum $A_{min}[k_i, k_i']$'s corresponding to vertex i, $i = 1, \cdots, n$. Hence, by Brent's scheduling principle[5][8], we can compute the minimum $A_{min}[k_i, k_i']$'s for $i = 1, \cdots, n$, in $O(\log n)$ time using $O(n/\log n)$ processors. The total complexity in step 5 is $O(\log n)$ time using $O(n/\log n)$ processors.

In step 6, we compute $\min\{\ M(i) \mid x \leq i \leq y\ \}$, where $x < y$, for each diagonal $e_j = (x, y)$, $j = 1, \cdots, k(= O(n))$. Since this process is equivalent to the process described in step 5, this can be done in $O(\log n)$ time using $O(n/\log n)$ processors.

Step 7 takes $O(\log n)$ time using $O(n/\log n)$ processors.

Having assumed that the input graph G is a biconnected graph so far, we shall describe, before closing this section, how to decide whether G is outerplanar when G is a general graph. We first check if G has at most $2n - 3$ edges. We next find biconnected components, that is, blocks $B_1, B_2, \cdots, B_k$ of G by applying the algorithm of finding biconnected components in [4] [9], which runs in $O(\log n)$ time using $O(n\alpha(l, n)/\log n)$ processors. If G is outerplanar, then each of blocks $B_1, B_2, \cdots, B_k$ is also outerplanar [2]. Thus, we independently execute Procedure Recognition for each of these blocks $B_1, B_2, \cdots, B_k$. If a block B_i is an edge, then Procedure Recognition tells that B_i is outerplanar. When each block B_i, $i = 1, \cdots, k$, is outerplanar, we print "G is outerplanar" and stop. By the above-mentioned statements, we have the following theorem.

Theorem 4 *Given a graph G with n vertices and m edges, whether G is outerplanar or not can be decided in $O(\log n)$ time using $O(n\alpha(l, n)/\log n)$ processors on the arbitrary-CRCW PRAM where $\alpha(l, n)$ is the inverse Ackermann function, which grows extremely slowly with respect to l and n [9] and $l = O(n)$.* □

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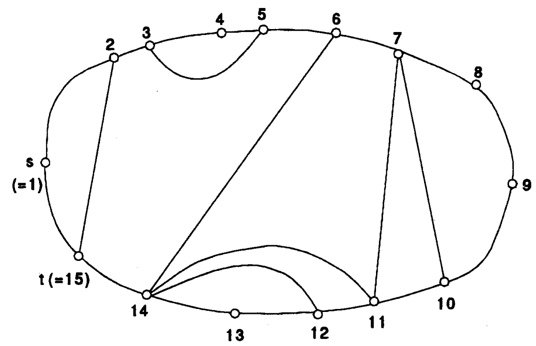

Figure 1: An example of an outerplanar graph.

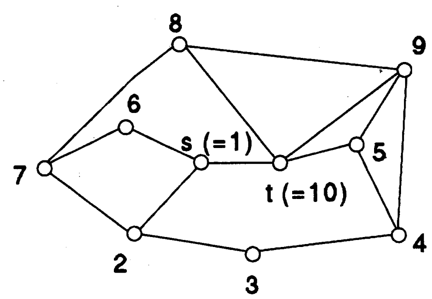

Figure 2: An example of *st*-numbering.

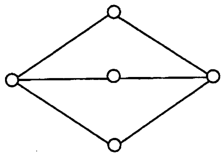

図 3: $K_{2,3}$.

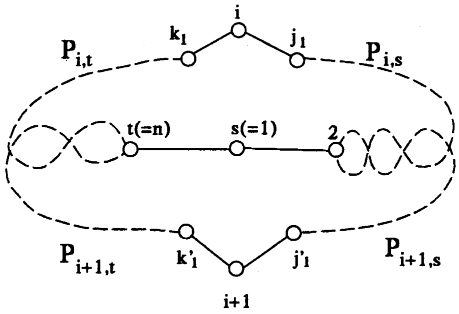

図 4: Illustration of the proof of Lemma 1.

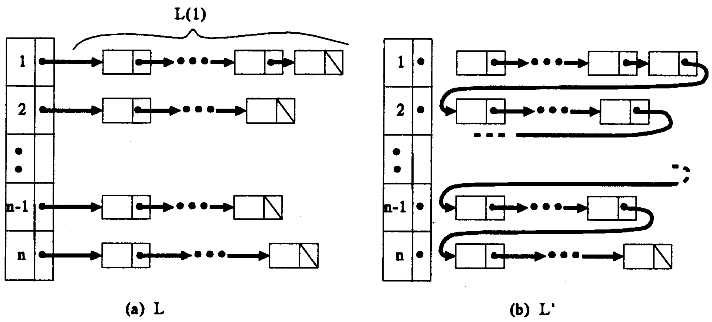

図 5: Adjacency lists $L(i)$, $i = 1, \cdots, n$, and linked list L'.

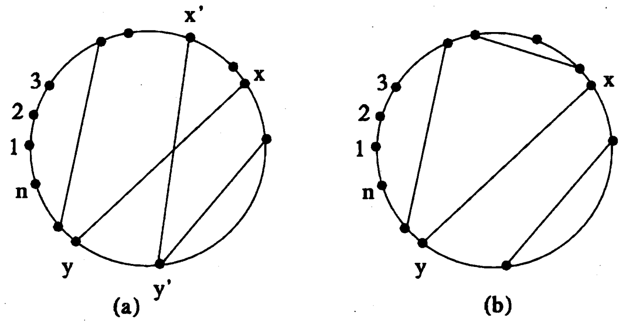

図 6: Illustration of the proof of Lemma 2.