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AN ALGORITHM FOR TESTING THE PLANARITY OF PARTIALLY ORIENTED GRAPHS

by

W.M. vanCleemput

(See back pages for 1473)

June 1977

Technical Note No. 116

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AN ALGORITHM FOR TESTING THE PLANARITY OF PARTIALLY ORIENTED GRAPHS

by

W.M. vanCleemput

ABSTRACT

An efficient algorithm will be presented for testing the planarity of oriented and partially oriented graphs. This algorithm is very useful for solving problems related to the circuit layout problem.

INDEX TERMS: graph theory, planarity, circuit layout problem, partially oriented graphs

This work was supported by the Joint Services Electronics Program under contract N-00014-75-C-0601.

1. INTRODUCTION

The problem of laying out printed circuits and integrated circuits shows a striking similarity with the problem of testing a graph for planarity [4].

In [2,3] a graph model for the circuit layout problem was presented. This model introduced the concept of a partially oriented graph.

A partially oriented graph is a triple (V,E,O) where V is the set of vertices, E is the set of edges and O is a collection of cyclic permutations of vertices that are adjacent to the same vertex.

An important step in obtaining an optimal layout of a circuit using graph-theoretical methods consists of testing the graph representation of the circuit for planarity.

In [5] an $O(|V|^2)$ algorithm for this problem was presented, where $|V|$ is the number of vertices of the graph model. This algorithm is based on the one by Lempel, Even and Cederbaum [9].

In this paper an algorithm, based on Tarjan's [1] algorithm for testing the planarity of simple (i.e. non-oriented) graphs will be presented. This new algorithm requires $O(|V|)$ steps, which is a significant improvement.

2. DEFINITIONS

All undefined theoretical concepts used in this paper follow Behzad and Chartrand [6] and Harary [7].

The following definitions concerning oriented graphs are adapted from [8]:

DEFINITION 1:

An oriented graph is a triple (V,E,O), where V is the set of vertices, E is a family of subsets of V of cardinality 2 and O is a collection of cyclic permutations of members of V, that are adjacent to the same vertex.□

In other words, if v is a member of V, then there exists in O, a member F, such that F is a cyclic permutation of the vertices of V, that are adjacent to v.

DEFINITION 2:

An oriented graph G is planar if it can be embedded in the plane such that for the arcs a(i) with a common endpoint P that correspond to the edges incident to a given vertex v, a clockwise sweep around P encounters these arcs a(i) in the order prescribed by the orientation.□

Let a,b and c be three adjacent edges incident to a vertex v; by b >< [a,c], we will indicate that a clockwise sweep around v encounters these three edges in the order a, b, c (i.e. b lies between a and c).

DEFINITION 3:

A planar oriented graph is outerplanar if it can be embedded such that every vertex of G lies on the boundary of some region (usually the exterior region).□

DEFINITION 4:

G is an oriented graph of type 1 if there exist in G two distinct vertices m and n and three paths p_1, p_2 and p_3, from n to m, such that each edge of G belongs to exactly one of these paths and if N_1, N_2 and N_3 are edges incident to n and belonging to p_1, p_2 and p_3 respectively and if M_1, M_2 and M_3 are edges incident to m and belonging to p_1, p_2 and p_3 respectively then N_1 >< $[N_2,N_2]$ if and only if M_1 >< $[M_1,M_2]$.□

An example of such a graph is given in Fig. 1(a).

DEFINITION 5:

G is an oriented graph of type 2 if there exists a vertex n and two cycles C_1 and C_2 such that each edge of G belongs to exactly one of the cycles and if vertex n is incident to edges M_1 and N_1 of cycle C_1 and to edges M_2 and N_2 of cycle C_2 then M_2 >< $[M_1,N_1]$ if and only if M_1 >< $[M_2,N_2]$.□

Fig. 1(b) shows an example of a graph of type 2.

Theorem 1: if G is a minimal non-planar subgraph of an oriented graph, then G is an oriented graph of type 1 or G is an oriented graph of type 2. [8].□

Testing an oriented graph for planarity, using this characterization is not practical.

DEFINITION 6:

A graph G(V,E,O) is partially oriented if for some v in V, there exists a cyclic permutation F that belongs to O.□

The following definitions, related to efficient algorithms are from [1].

DEFINITION 7:

The adjacency list of a vertex v is an unordered list of the vertices, adjacent to v.□

DEFINITION 8:

The adjacency structure A of a graph G is the collection of adjacency lists for all vertices of G.□

DEFINITION 9:

In a directed graph, v is an ancestor of w and w is a descendant of v if there exists a path from v to w. If the path is of length 1, then v is the father of w and w is the son of v.□

3. TARJAN'S ALGORITHM

Tarjan's algorithm [1] forms the basis for the algorithm, described in section 4. It is required that the graph being tested is 2-connected. The graph is specified in the form of an adjacency structure A.

Tarjan's algorithm is linear in $|V(G)|$. If the graph is not 2-connected, then it can be decomposed into 2-connected components in $O(|V|)$ time and the planarity of each of these 2-connected components has to be tested separately.

4. PLANARITY TESTING FOR PARTIALLY ORIENTED GRAPHS

This section is concerned with an extension to Tarjan's algorithm for testing the planarity of a partially oriented graph G in linear time. We can reduce the problem to testing the planarity of partially oriented graphs with oriented vertices of valency 3 only. This can be accomplished by replacing every oriented vertex of valency n, greater than 3, by a cycle with n new orinted vertices of valency 3, as illustrated in Fig. 2.

Let G' be the partially oriented graph, obtained by this transformation. Then the following holds.

Theorem 2: G' is planar if and only if G is planar.

Proof: a) suppose G' is planar. Then G can be obtained from G' by contracting the cycles that replaced the oriented vertices of valency greater than 3. Then G is planar.

b) if G is planar, then G' is planar. If G is planar, then there exists a cycle basis Z(1),...Z(m) and a cycle Z(0) in G, such that every edge of G belongs to exactly two of these cycles (MacLane), Then, because of the transformation defined, there exists a cycle basis Z'(1), ...,Z'(n) and a cycle Z'(0) in G', such that every edge of G' belongs to exactly two of these cycles.

For most circuit layout graphs, oriented vertices will be of valency 3. If not, it will be assumed that the component models have been transformed such that this property holds.

It can easily be verified that $|E(G')| \leq |E(G)|$ *and that* $|V(G')| \leq 2.\ E(G)$. Therefore, if $|E(G)| = k.|V(G)|$ then $|E(G')| = k'.|V(G')|$.

The following algorithm is a modification of Tarjan's algorithm. It allows one to test the planarity of a partially oriented graph G(V,E) with oriented vertices of valency 3 only, in time proportional to $|V|$ if $|E| = k.|V|$.

Steps 1-3 are essentially the same as in Tarjan's algorithm.

(1) Apply a depth-first search to G, starting from some (arbitrarily chosen) vertex s. This search imposes a direction upon the edges of G, depending on the order in which its end-vertices were reached by the search. By doing so, G is transformed into a directed graph G', whose edges are partitioned into a set of edges, forming a spanning tree, and a set of fronds. The directed graph G' is called a palm tree

(2) Reorder the adjacency structure, using the information

collected in the first step. This is done using a radix sort.
(3) Perform a depth-first search on the new adjacency structure, thereby partitioning G into a set of edge-disjoint paths. Let $p = (s,\ldots,f)$ be a path and let $p_0 = (s_0,\ldots,f_0)$ be the first path containing s. Then p is a special path if $f = f_0$ and a normal path otherwise.
(4) Examine all paths $p = (s,\ldots,f)$. If s is an oriented vertex, then determine on which side (Left or Right) p has to be embedded in order to satisfy the orientation imposed around s. If f is oriented, then determine on which side the frond has to descend. We can represent this as a function SIDE(p,v) with possible values L(eft), R(ight) and U(ndefined). SIDE(p,v) = U if vertex is not oriented.

First assume that p is a normal path. Then the frond of p has to descend on the same side as the embedding of the path. The following decision table indicates the action to be taken for each possible case.

SIDE(p,f) \ SIDE(p,s)	L	R	U
L	l	n	l
R	n	r	r
U	l	r	u

where l: embed p on the left.
r: embed p on the right.
u: p can be embedded on both sides.
n: the graph is non planar.

If $p = (s,\ldots,f)$ is a special path, then its frond has to descend on the same side as the frond of p_0, i.e. the path on which s debuts, unless $f=f_0=1$. However, if $f\neq 1$ then the valency of f must be at least 4 and therefore f cannot be an oriented vertex. If f=1 and oriented, then we can require without loss of generality that the frond of p descend on the same side as the path's embedding (similar to normal paths). The only case left for special paths is when s is an oriented vertex. Then the embedding of p is determined by SIDE(p,s).

5) Build a dependency graph. This step is essentially the same as in Tarjan's algorithm. Embed the first path (a circuit) in the plane as a polygon. Try to embed the other paths, in the order in which they were generated in step 3), one at a time. Each new path has exactly two points in common with the already embedded subgraph. Certain paths have to be embedded in different faces or in the same face, with respect to other paths. This relationship between paths can be represented by a dependency graph. Tarjan proves that it is sufficient to construct only a subgraph of this dependency graph, for which the number of edges is a linear function of V(G) .

6) Try to bicolor the dependency graph DG, using the colors L(eft) and R(ight). DG consists of one or more disconnected components. The difference with Tarjan's algorithm is that there are a number of vertices in V(DG) that have preassigned colors. Every vertex in V(DG) represents a path in the original graph. The bicoloring procedure consists of the following major steps.

- mark all vertices as unexplored.
- find a colored, but not explored vertex and mark it as explored. If no such vertex exists, then find an unexplored vertex and assign it any color (e.g. L). If all vertices have been explored, then DG can be colored with 2 colors and hence G is planar.
- use a depth-first search to explore the component of DG, containing the selected start-vertex: each time a vertex is reached, check whether it is colored or not. If not,

assign it the appropriate color. If it was already colored, check the colors: if they are compatible, continue; if not, the graph G is non-planar.

The procedure for enforcing the embedding of paths (step 4) requires $O(|E|)$ time for general graphs and $O(|V|)$ time if $|E| = k.|V|$. Bicoloring the dependency graph requires time proportional to the number of edges in E(DG). If a dependency subgraph was constructed and if $|E| = k.|V|$ then $|E(DG)| = O(|V|)$ and the time required for testing the planarity of G is $O(|V|)$.

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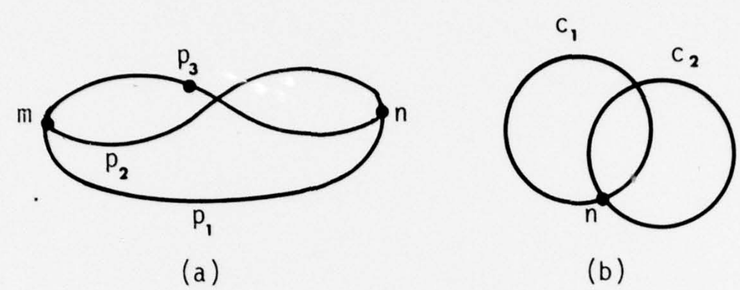

FIGURE 1 (a) Oriented graph of type 1.
(b) Oriented graph of type 2.

FIGURE 2 Replacing an oriented vertex of valency n by oriented vertices of valency 3.

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