1989

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Report Number:
88-813

http://docs.lib.purdue.edu/cstech/692

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AN OPTIMAL PARALLEL ALGORITHM FOR
THE MINIMUM CIRCLE-COVER PROBLEM

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CSD-TR-813
September 1989
(Revised April 1989)
An Optimal Parallel Algorithm for the Minimum Circle-Cover Problem

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Abstract

Given a set of $n$ circular-arcs, the problem of finding a minimum number of circular-arcs whose union covers the whole circle has been considered both in sequential and parallel computational models. Here we present a parallel algorithm in the EREW PRAM model that runs in $O(\log n)$ time using $O(n)$ processors if the arcs are not given already sorted, and using $O(n/\log n)$ processors otherwise. Our algorithm is optimal since the problem has an $\Omega(n\log n)$ lower bound for the unsorted arcs case, and an $\Omega(n)$ lower bound for the sorted arcs case. The previous best known parallel algorithm runs in $O(\log n)$ time using $O(n^2)$ processors, in the worst case, in the CREW PRAM model.

Keywords: Analysis of algorithms, circle-cover, combinatorial problems, computational geometry, parallel processing.

1 Introduction

Let $S = \{A_1, A_2, \ldots, A_n\}$ be a set of $n$ circular-arcs on a circle $C$. The minimum circle-cover problem is to find a minimum number of circular-arcs whose union covers $C$. This problem was considered in references [1,6], where one practical application was mentioned. Another possible application is in scheduling workers so that at least one worker is on the job at any time (the circle then represents the 24 hours in one day, each circular-arc represents the period of time during which a particular worker is willing to work, and the goal is to use as few different workers as possible).

In this paper, we present an efficient parallel algorithm for the minimum circle-cover problem.

Lee and Lee [5] gave an $O(n\log n)$ time sequential algorithm for unsorted $S$ and a linear time algorithm for sorted $S$, and they showed that their algorithms are optimal. Bertossi [1], later,
provided a parallel algorithm in the CREW PRAM computational model (recall that this is the model where the processors, which operate synchronously, share a common memory, and are allowed to concurrently read from the same memory cell but are not allowed to simultaneously write to the same memory cell). The algorithm in [1] runs in $O(\log n)$ time using $O(n^2/\log n + qn)$ processors, where $q - 1$ is the minimum number of arcs crossing any point of the circle. In the worst case, Bertossi's algorithm uses $O(n^2)$ processors, and its time $\times$ processor product is $O(n^2 \log n)$.

The computational model for our algorithm is the EREW PRAM model (Exclusive Read Exclusive Write Parallel Random Access Machine), which differs from the CREW PRAM in that even concurrent reading from a memory cell is disallowed. Thus, this computational model is less powerful than that in [1]. Our algorithm runs in $O(\log n)$ time using $O(n)$ processors for unsorted $S$ and using $O(n/\log n)$ processors for sorted $S$. Therefore, our algorithm is obviously optimal since its time and processor products match the lower bounds given in [6].

In the next section, we give the notations and some preliminary observations, and we outline the main steps of the algorithm. Section 3 describes the preprocessing steps, and Section 4 presents the algorithm.

2 Preliminaries

The input to the algorithm consists of a set $S = \{A_1, A_2, \ldots, A_n\}$, where each $A_i$ is a circular-arc on a circle $C$ (a circular-arc on $C$ is a contiguous portion of the circumference of $C$). Each $A_i$ is specified by an ordered pair $[x_i, y_i]$, where $x_i$ and $y_i$ are the two endpoints of $A_i$, such that $A_i$ is drawn by moving the pen clockwise from $x_i$ to $y_i$; point $x_i$ is then called the first endpoint of $A_i$, and $y_i$ is called the second endpoint of $A_i$. Without loss of generality, we assume that no single arc $A_i$ covers the whole circle $C$. To avoid cluttering the exposition, we also assume that no two input arcs have the same endpoint (i.e., the $2n$ endpoints are distinct). Our algorithm can easily be modified for the general case. We sort the $2n$ endpoints of the arcs in $S$ such that we encounter the endpoints in increasing order if we start at $x_1$ and travel along $C$ in the clockwise direction. This sorting can be done in $O(\log n)$ time using $O(n)$ processors in the EREW PRAM model [2]. From now on, we assume that the $2n$ endpoints in $S$ are available in this sorted order. We also assume that the arcs in $S$ have been relabeled such that $i < j$ implies that $x_i$ occurs before $x_j$ in the sorted array of endpoints. This relabeling is easily implemented by a parallel prefix computation (for the sake of completeness, the definition of parallel prefix is reviewed below).

Lemma 2.1 Let $M$ be an array of elements, $M = \{m_1, m_2, \ldots, m_n\}$. Let parallel prefix be the problem of computing all the partial sums $s_i = m_1 \oplus m_2 \oplus \cdots \oplus m_i$, where $\oplus$ is an associative operation. The parallel prefix problem can be solved in $O(\log n)$ time using $O(n/\log n)$ processors on an EREW PRAM.

Proof: See [4,5].
If $A_i \cap A_j = A_j$, and $i \neq j$, we say that $A_j$ is contained in $A_i$. It is easy to see that those arcs that are contained in some other arcs can be ignored, since there is always a minimum cover for $C$ that does not use any of them. Thus in the rest of this section, we assume that no arc in $S$ is contained in some other arc (we call this the noncontainment property). A preprocessing procedure for removing all contained arcs in $S$ is given later, in Section 3. The following was observed in [6] (for notational convenience, $y_{n+1} = y_1$).

**Lemma 2.2** If the noncontainment property holds, then for any $i \in \{1, 2, \ldots, n\}$, if we start at $y_i$ and move clockwise along $C$, then the first $y_j$ ($j \neq i$) that we encounter is $y_{i+1}$.

**Proof:** Suppose not, i.e., suppose we encounter a $y_j$ with $j \neq i+1$. Then we distinguish two cases:
(i) if a clockwise trip from $x_i$ to $y_j$ encounters $x_j$ then $A_j$ is contained in $A_{i+1}$ and this contradicts the noncontainment property; (ii) if a clockwise trip from $x_i$ to $y_j$ does not encounter $x_j$ then $A_i$ is contained in $A_j$ and this also contradicts the noncontainment property. \(\square\)

Therefore, in the clockwise direction of $C$, the next $x_j$ encountered after $x_i$ is $x_{i+1}$, and the next $y_j$ encountered after $y_i$ is $y_{i+1}$.

As in [6], we define a function $SUC: S \rightarrow S$, called successor, as follows: $SUC(A_i) = A_j$, if and only if $x_j$ is the last of the $x_k$'s encountered by a clockwise sweep from $x_i$ to $y_i$ (possibly it is $x_i$ itself). Note that this implies that $SUC(A_i)$ and $A_i$ overlap. If $SUC(A_i) = A_i$ then we can obviously conclude that there is no cover for $C$ from the arcs of $S$. We define the inverse of $SUC$, $SUC^{-1}$, by $SUC^{-1}(A_i) = \{A_i \in S \mid SUC(A_i) = A_j\}$. Obviously, we can have $|SUC^{-1}(A_j)| > 1$. The computation of $SUC$ and $SUC^{-1}$ is given in Section 3.

The outline of our algorithm is now given. The details of implementing the steps below are described in Section 3 and Section 4.

**Algorithm Min-Cover($S$, flag)**

**Input:** A set $S = \{A_1, A_2, \ldots, A_n\}$ of $n$ circular-arcs on circle $C$, each of which is specified by its two endpoints. The integer flag is 1 if the endpoints of the arcs in $S$ are given sorted, and 0 otherwise.

**Output:** A subset of $S$ whose arcs form a minimum cover for $C$.

The main steps:

1. If flag is 0, then sort the endpoints of the arcs in $S$.
2. Eliminate all contained arcs in $S$ (Section 3).
3. Compute $SUC(A_j)$ for each $A_j \in S$ (Section 3). If for some $A_j$, $SUC(A_j) = A_j$, then report "no cover exists in $S" and stop the algorithm.
4. Compute $SUC^{-1}(A_j)$ for every $A_j \in S$ (Section 3).
(5) Execute the main procedure to find and report a minimum cover (Section 4).

end.

Theorem 2.3 Given a set \( S \) of \( n \) circular-arcs on a circle, algorithm Min-Cover solves the minimum circle-cover problem in \( O(\log n) \) time using \( O(n/\log n) \) processors in the EREW PRAM model if the set of endpoints of the arcs in \( S \) is given sorted, and using \( O(n) \) processors otherwise. The algorithm is optimal to within a constant factor.

Proof: The optimality follows from the lower bounds shown in [6]. The correctness and the time and processor complexities follow from the descriptions to be presented in Section 3 and Section 4.

\( \square \)

3 Preprocessing

In this section, we show how to perform three preprocessing tasks: (i) the elimination of contained arcs; (ii) computing the \( SUC \) function; (iii) computing \( SUC^{-1} \). We assume that we are given, in addition to the set of arcs \( S \), the sorted array \( E \) containing the \( 2n \) endpoints of the arcs in \( S \). These appear in \( E \) in the same order they are encountered by a clockwise scan of the circle, beginning at \( z_1 \). We show in what follows that tasks (i)-(iii) can each be done in \( O(\log n) \) time using \( O(n/\log n) \) processors, in the EREW PRAM model.

3.1 Eliminating Contained Arcs

This subsection describes the procedure for eliminating contained arcs. Let the rank of an endpoint in the array \( E \) be \( i \) iff it occupies position \( i \) in \( E \). Let \( W \) denote the set of arcs in \( S - \{A_1\} \) that contain \( z_1 \). Let \( y^\prime \) denote the largest-ranked (in \( E \)) \( y_j \) for which \( A_j \in W \). For the example of Figure 1a, \( y^\prime \) is \( y_8 \), whose rank in \( E \) is 5. Remove from \( S \) every arc \( A_i \) that is contained in the portion of the circle going from \( z_1 \) (clockwise) to \( y^\prime \) (such an arc is surely contained in some arc in \( W \)), then update \( E \) by deleting from it the endpoints of the arcs so removed. The rest of this subsection assumes that this has already been done (and \( S \) and \( E \) modified accordingly). For the example of Figure 1a, arc \( A_2 \) is removed because it is contained in the portion of the circle going clockwise from \( z_1 \) to \( y_8 \), resulting in Figure 1b.

Let \( E_1 \) be obtained from \( E \) by removing from it every \( y_j \) for which \( A_j \in W \). Let \( E_2 \) be obtained from \( E \) by only keeping in it the \( y_j \)'s for which \( A_j \in W \). Let \( E_1E_2 \) denote the concatenation of \( E_1 \) with \( E_2 \). For the situation of Figure 1b, we would get

\[ E_1E_2 = x_1x_2y_1x_4y_3x_5y_6x_7y_5x_8y_4y_9y_8. \]

Intuitively, what we are doing by constructing \( E_1E_2 \) is "linearizing" the circular problem by "unrolling" it on a line. If \( W \) were empty then clearly we would achieve this by simply "opening"
the circle (i.e., cutting it open) at \( x_1 \). In other words, if \( W \) is empty then the array \( E \) already constitutes a linearization of the circular problem (in fact, \( E_1 E_2 \) equals \( E \) in that case). However, if \( W \) is not empty then the way to linearize the problem is to make two clockwise trips around the circle, starting from position \( x_1 \): during the first trip we only look at the endpoints of the arcs in \( S - W \) and at the first endpoints of the arcs in \( W \), while in the second trip we only look at the second endpoints of the arcs in \( W \). Thus the first trip sees the sequence \( E_1 \), while the second trip sees \( E_2 \).

The sequence \( E_1 E_2 \) has the property that an arc \( A_i \) is contained if and only if it is contained in the linear (i.e., noncircular) sequence \( E_1 E_2 \). In other words, \( A_i \) is contained if and only if there exists a \( j \) such that, in \( E_1 E_2 \), \( x_j \) occurs before \( x_i \) and \( y_j \) occurs after \( y_i \). We now turn our attention to the detailed implementation of these ideas.

Clearly, we can obtain each of \( W \), \( E_1 \), \( E_2 \), and \( E_1 E_2 \) in \( O(\log n) \) time and \( O(n/\log n) \) EREW PRAM processors, by using parallel prefix.

Once we have \( E_1 E_2 \), eliminating contained arcs is done as follows.

1. Using parallel prefix, compute for each element of \( E_1 E_2 \) its rank in array \( E_1 E_2 \). For the example we are using, the rank of \( y_5 \) is 11.

2. Assign to every \( x_i \) in \( E_1 E_2 \) a weight equal to the rank of \( y_i \) in \( E_1 E_2 \). For the example we are using, the weight of \( x_5 \) is 11.

3. Assign to every \( y_i \) in \( E_1 E_2 \) a weight of zero.

4. Do a parallel prefix on the weighted array \( E_1 E_2 \) to find, for every \( x_i \), the largest weight that occurs before it. If that weight is larger than \( x_i \)’s own weight then \( A_i \) is contained; otherwise it is not.
(5) Remove all contained arcs from \( S \), and delete their endpoints from \( E \).

(6) Relabel the surviving arcs in \( S \) so that their indices are in consecutive order (i.e., \( A_1, A_2, \ldots \)).

Correctness of the above procedure follows from the discussion in the paragraph preceding it. Its time and processor complexities are those of parallel prefix: \( O(\log n) \) time and \( O(n/\log n) \) EREW PRAM processors.

From this point on we assume that we have already performed the above procedure for eliminating the contained arcs from \( S \) and relabeling the surviving arcs in \( S \) so that their indices are in consecutive order. For simplicity of notation, we still use \( n \) to denote the number of arcs in \( S \).

3.2 Computing the \( SUC \) Function

We compute the \( SUC \) function as follows.

(1) In the array \( E \), let the weight of each \( x_i \) be \( i \), and let the weight of every \( y_i \) be zero.

(2) Do a parallel prefix on the weighted \( E \) to find, for every \( y_i \), the largest weight that occurs before it in \( E \). If that weight is (say) \( j \) for a particular \( y_i \), then \( SUC(A_i) = A_j \).

Correctness of the above procedure follows from the fact that the largest weight that occurs before \( y_i \) in \( E \) is the subscript \( j \) of \( x_j \) such that \( x_j \in A_i \) and the clockwise sweep from \( x_j \) to \( y_i \) encounters no other \( x_k \) (possibly \( j = i \)). It can clearly be implemented in \( O(\log n) \) time using \( O(n/\log n) \) EREW PRAM processors.

After the \( SUC \) function has been computed, we check whether for some \( i \) we have \( SUC(A_i) = A_i \). If so then we immediately stop and decide that there is no circle cover (because in that case the portion of the circle immediately after \( y_i \) in the clockwise direction is not covered by any arc). Otherwise, we proceed to find a minimum cover of \( C \) as explained in the rest of this paper. (This test is easily done in \( O(\log n) \) time using \( O(n/\log n) \) EREW PRAM processors.)

3.3 Computing \( SUC^{-1} \)

Recall that for every \( A_j \), \( SUC^{-1}(A_j) = \{ A_i \in S \mid SUC(A_i) = A_j \} \). The next lemma is useful in computing \( SUC^{-1} \) efficiently.

Lemma 3.1 Let \( A_i \) and \( A_j \) be such that \( x_j \) occurs on \( A_i \), and \( SUC(A_i) = SUC(A_j) \). Let \( A_i \) be such that \( x_i \) occurs on \( A_i - A_j \) (i.e., on the portion of \( A_i \) that is not covered by \( A_j \)). Then \( SUC(A_i) = SUC(A_i) \).

Proof: Since \( x_i \) occurs on \( A_i - A_j \), by Lemma 2.2, \( y_i \) must occur on \( A_j - A_i \). This and the fact that \( SUC(A_i) = SUC(A_j) \) imply that \( SUC(A_i) = SUC(A_i) \). \( \Box \)

The above lemma implies that for every \( A_j \), the arcs in \( SUC^{-1}(A_j) \) occur around \( C \) consecutively. Therefore we can compute \( SUC^{-1} \) in \( O(\log n) \) time using \( O(n/\log n) \) EREW PRAM processors simply by "marking" on \( S \) the indices \( i \) at which \( SUC(A_i) \neq SUC(A_{i+1}) \). More specifically,
we compute for each \( j \) the pair \((l_j, r_j)\) such that \( SUC^{-1}(A_j) = \{A_{l_j}, A_{l_j+1}, \ldots, A_{r_j}\} \), with the notational convention that \( A_{n+i} = A_i \) for every \( i \in \{1, 2, \ldots, n\} \). This is done as follows.

(1) For every \( A_i \), initialize \( SUC^{-1}(A_i) = \emptyset \).

(2) For every \( i \), compare \( SUC(A_i) \) and \( SUC(A_{i+1}) \): if \( SUC(A_i) = A_j \neq SUC(A_{i+1}) = A_k \), then we set \( r_j = i \) and \( l_k = i + 1 \).

Note also that, given the pair \((l_i, r_i)\), one processor can easily obtain \(|SUC^{-1}(A_i)|\) in constant time.

4 The Main Procedure

After the preprocessing of Section 3, the noncontainment property of \( S \) is ensured and \( SUC \) and \( SUC^{-1} \) are available. Using \( SUC \) and \( SUC^{-1} \), we compute the minimum cover of \( C \) from \( S \) in the main procedure, which is described in this section.

A greedy algorithm for finding a cover of \( C \) is given in [6], and when started at \( A_j \), it produces a (not necessarily optimal) cover \( S(A_j) \) of \( C \) as follows:

\[
\begin{align*}
&\text{let } S(A_j) = \{A_j\}, \\
&B = A_j; \\
&\text{while } S(A_j) \text{ does not form a cover do} \\
&\quad \text{let } B = SUC(B); \\
&\quad \text{add } B \text{ to } S(A_j); \\
&\text{end while.}
\end{align*}
\]

In what follows we shall use \( S(A_j) \) to denote the cover produced when the above greedy procedure terminates. Again, we let \( W \) be the set of arcs in \( S - \{A_1\} \) that contain \( \pi_1 \).

Lemma 4.1 For some \( A_i \in W \), \( S(A_i) \) is a minimum cover.

Proof: Easy, and omitted. \( \square \)

Thus our problem is that of simulating, in parallel for all \( A_i \in W \), the sequential greedy algorithm. Once we have \( S(A_i) \) for all \( A_i \in W \), we choose a minimum-cardinality \( S(A_i) \) as our minimum cover. This is done as follows.

Create a new copy of each \( A_i \in W \), denoted by \( New(A_i) \) (without discarding the old copy \( A_i \)). Let \( New(W) \) denote the set of new copies of the elements in \( W \). Then we modify the \( SUC \) function by replacing every \( SUC(A_j) = A_i \), where \( A_i \in W \), with \( SUC(A_j) = New(A_i) \), and for every \( New(A_i) \) setting \( SUC(New(A_i)) \) equal to \( \emptyset \). Figure 2b depicts the modified \( SUC \) function corresponding to Figure 2a. This new \( SUC \) function defines an in-forest \( F \) in which \( SUC(A_k) \) is the parent of \( A_k \). There are \(|W| \) trees in \( F \), whose roots are the elements of \( New(W) \),
and whose leaves include all the elements of $W$, as well as other leaves. For every node $A_k$ of $F$, let $\text{Root}(A_k)$ be the element of $\text{New}(W)$ that is at the root of the tree containing $A_k$, let $\text{ChildRoot}(A_k)$ be the child of $\text{Root}(A_k)$ that is ancestor of $A_k$, and let $\text{Depth}(A_k)$ be the depth of $A_k$ in its tree (i.e., the number of nodes on the $A_k$ to $\text{Root}(A_k)$ path in $F$). For example, in Figure 2, $\text{Root}(A_6) = \text{Root}(A_7) = \text{New}(A_6)$, and $\text{ChildRoot}(A_6) = \text{ChildRoot}(A_7) = A_5$. Before proceeding with the exposition, let us observe that the arrays $\text{Root}$, $\text{ChildRoot}$, and $\text{Depth}$ can easily be computed in $O(\log n)$ time and with $O(n/\log n)$ EREW PRAM processors using the Euler Tour technique [7] in conjunction with optimal parallel list-ranking [3] (we can use the Euler Tour technique because we have $\text{suc}^{-1}$, which provides the list of children for every node in $F$). Assume that this has already been done.

Now, for each node (say, $A_k$) of $F$, tag that node as being "good" or "bad" according to the following rule: if $A_k \in W$, then $A_k$ is good; otherwise it is bad. Thus $A_k$ is bad if it is not a leaf, or a leaf that is not in $W$. The good nodes in Figure 2b are circled. Every good leaf $A_k$ can tell the value of $|S(A_k)|$ by testing whether the second endpoint of $\text{ChildRoot}(A_k)$ occurs on $A_k$ or not: if the second endpoint of $\text{ChildRoot}(A_k)$ does not occur on $A_k$, then $|S(A_k)| = \text{Depth}(A_k)$ and $S(A_k)$ is the $A_k$ to $\text{Root}(A_k)$ path in $F$; otherwise $|S(A_k)| = \text{Depth}(A_k) - 1$ and $S(A_k)$ is the $A_k$ to $\text{ChildRoot}(A_k)$ path in $F$. In Figure 2, $A_7$ is an example of the first case ($|S(A_7)| = \text{Depth}(A_7) = 5$), while $A_6$ is an example of the second case ($|S(A_6)| = \text{Depth}(A_6) - 1 = 4$). It follows from these remarks that obtaining an $A_k \in W$ that has a minimum $|S(A_k)|$ is easily done in $O(\log n)$ time and with $O(n/\log n)$ EREW PRAM processors. Once we have such an $A_k$, its $S(A_k)$ (which is a minimum cover) can easily be retrieved using the same time and processor bounds, since it is defined by a path in $F$ and can thus be traced using (again) the Euler Tour technique [7] in conjunction with optimal parallel list-ranking [3].
5 Conclusion

We gave a parallel algorithm in the EREW PRAM computational model for the minimum circle-cover problem. Our algorithm runs in $O(\log n)$ time using $O(n)$ processors if the input arcs are not sorted and using $O(n/\log n)$ processors otherwise. Since the time and processor products of our algorithm are within a constant factor of the sequential lower bounds ($\Omega(n \log n)$ for unsorted arcs and $\Omega(n)$ for sorted arcs), this algorithm is optimal. The previous best known parallel algorithm runs in $O(\log n)$ time using in the worst case $O(n^2)$ processors in the (stronger) CREW PRAM computational model. Hence, our solution improves the processor complexity by a factor of $n$, and by using a less powerful computational model.

Acknowledgement. The authors are grateful to an anonymous referee for his useful comments.

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