Efficient Self-stabilizing Algorithms for Tree Networks

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Abstract

Many proposed self-stabilizing algorithms require an exponential number of moves before stabilizing on a global solution, including some rooting algorithms for tree networks [1, 2, 3]. These results are vastly improved upon in [5] with tree rooting algorithms that require only $O(n^3 + n^2 \cdot c_h)$ moves, where n is the number of nodes in the network and c_h is the highest initial value of a variable. In the current paper, we describe a new set of tree rooting algorithms that brings the complexity down to $O(n^2)$ moves. This not only reduces the first term by an order of magnitude, but also reduces the second term by an unbounded factor. We further show a generic mapping that can be used to instantiate an efficient self-stabilizing tree algorithm from any traditional sequential tree algorithm that makes a single bottom-up pass through a rooted tree. The new generic mapping improves on the complexity of the technique presented in [7].

1 Introduction

A distributed system can be modeled as an undirected graph $G = (V, E)$, where V is the set of n systems, or nodes, and E is the set of links, or edges, interconnecting the systems together. In the self-stabilizing algorithmic paradigm, each node can only see its neighbors and itself, yet the system of simultaneously running algorithms must converge to a global state satisfying some desired property. Problems that are typically straight-forward to solve using a sequential algorithm often require far more clever approaches in the self-stabilizing paradigm. In the next section we describe more completely the self-stabilizing algorithmic paradigm.

Numerous results in the literature address the issue of self-stabilizing algorithms for rooting a tree. In [1], [2] and [3] the authors describe tree algorithms for leader election, center-finding and median-finding, respectively. All three algorithms appear to require an exponential number of moves in the worst case. These results are vastly improved upon by the center-finding and median-finding algorithms in [5], both of which require only $O(n^3+n^2\cdot c_h)$ moves, where c_h is the highest initial value of the variables used in the computation. We improve further on these results by describing a generic self-stabilizing tree rooting algorithm that requires only $O(n^2)$ moves. This new generic algorithm can be used to solve, among others, the problems

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of electing a leader in a tree, finding the center of a tree and finding the median of a tree. Section 3 defines these and other graph properties, gives the generic tree rooting algorithm and shows how to choose a leader based on various criteria.

There are numerous graph problems that can be solved on a tree once the tree is rooted. Many self-stabilizing algorithms in the literature rely on this, augmenting an arbitrary tree rooting algorithm to solve one or another problem. See, for example, [4, 9, 11, 12]. In a seminal work, the authors of [7][1] present a unified approach to translating linear-time bottom-up sequential dynamic programming tree algorithms into self-stabilizing tree algorithms. Their technique can easily be applied to improve the results of [4, 11, 12]. The analysis in [7] uses round complexity, showing that the resulting tree algorithms require $2r + 3$ rounds, for a tree of radius r. It is easy to see that a single round could require as much as $O(n^2 + n \cdot c_h)$ moves, where c_h is again the highest initial value. Thus, they have described a set of self-stabilizing tree algorithms that run in $O(n^3 + n^2 \cdot c_h)$ moves. In Section 4 we present an improved generic mapping from sequential bottom-up one-pass tree algorithms to a self-stabilizing tree algorithm that requires only $O(n^2)$ moves. Included in that section is an example of instantiating a self-stabilizing algorithm, in this case to find a maximum independent set in a tree.

The fundamental idea used for all of the results in this paper is the time-honored concept of using a little additional storage in order to drastically reduce the computation time. Where previous algorithms would have used n variables, one per node in the network, we use $2n-2$ variables, two per edge in the network. Our algorithms have the added benefit of greatly simplified proofs of correctness.

Section 5 contains a brief discussion of the fundamental difference between our self-stabilizing algorithmic approach and that of the previously published tree algorithms.

2 The Self-Stabilizing Paradigm

Self-stabilizing algorithms were first introduced by Dijkstra as a way for a distributed system to reach a stable state regardless of its initial illegitimate state [6]. Later Lamport explored the idea of using self-stabilizing algorithms as a way of providing a safeguard against transient failures in fault tolerance [13]; a self-stabilizing system will automatically correct itself in the presence of intermittent faults.

A distributed system is modeled as undirected graph $G = (V, E)$, where V is a set of n nodes and E is a set of m edges. If i is a node, then $N(i)$, its *open neighborhood*, denotes the set of nodes to which i is adjacent. Every node $j \in N(i)$ is called a *neighbor* of node i. The set $N[i] = N(i) \cup \{i\}$ is the *closed neighborhood* of i. The *induced subgraph* $G - i$ is the subgraph of G induced by the nodes in $V - \{i\}$.

In a *self-stabilizing algorithm*, each node can change the value of its local variables based only on the value of the local variables in its closed neighborhood. The contents of a node's local variables constitute its *local state*. The system's *global state* is the union of all local states. No assumptions can be made about the initial global state; that is, the initial value of every local variable is arbitary. A node i changes its local state by making a *move*, i.e., changing the value of one or more of its local variables.

[1] Also to appear as [10].

Self-stabilizing algorithms are often given as a set of rules of the form "**if** $p(i)$ **then** $m(i)$," where $p(i)$ is a predicate and $m(i)$ is a move. The predicate $p(i)$ is defined in terms of the local state of i and the local states of its neighbors $j \in N(i)$. Every node in the system G runs the same set of rules. A node i is *privileged* if at least one of its rule-predicates is true. When a node is privileged, it may execute one of its privileged moves. No assumptions can be made about which privileged move is made when more than one exists. We say the system has *stabilized* if no nodes are privileged.

Analysis of a self-stabilizing algorithm is slightly different than that of a sequential algorithm. For self-stabilizing algorithms it is not the overall time-complexity that is of concern, but rather the number of moves made by the algorithm. That is, the time required to perform checks for predicates or to make updates to local variable values does not matter. The self-stabilizing algorithm is evaluated based only on the number of rules that are fired, or equivalently the number of moves made.[2]

As is common for self-stabilizing algorithms, we will assume that each node has a unique identifier. We will discuss in the conclusion how our algorithms can be modified to not require unique identifiers.

Many self-stabilizing algorithms work correctly only in the presence of a central daemon that serializes the moves made by privileged nodes [6]. Our algorithms do not rely on this restriction. We only assume read-write atomicity. Thus, two or more nodes can make simultaneous moves, as long as no node is accessing a value that is being written by another node.

3 A Generic Leader Election Algorithm

An important problem in distributed computing is that of electing the leader in a graph. When the graph is a tree this is equivalent to designating the root of a tree. We will assume throughout the remainder of this paper that the graph G is a tree. In this section we describe a generic self-stabilizing leader election algorithm for trees.

The generic algorithm can be instantiated with any rooting property that is based on a distance-from-the-leaves property of the nodes in the tree, as long as a tree can have only one "winner" (or two "winners", if the two can each detect the presence of a second) with the best distance-from-the-leaves. The following is a partial list of such properties.

- Maximum distance to a leaf. The *center* of a tree is a node whose maximum distance to a leaf is minimum. A tree has either a unique center or two adjacent centers[8].

- Sum of distances to all other nodes. The *median* of a tree is a node for which the sum of the distances from it to all other nodes is minimum. A tree has

[2]Some works have evaluated the round-complexity of a self-stabilizing algorithm, rather than the number of moves made. The focus then is on the number of rounds made by the self-stabilizing algorithm. A round is defined as follows. A node i is said to be alive in a round if there exists an execution sequence starting from the global state at the beginning of the round that contains a move made by i. A round is a minimal prefix sequence of moves made for which every alive node has made at least one move.

either a unique median or two adjacent medians[8].

- Size of largest disconnected component after removal. An $\frac{n}{2}$-*separator* of a tree is a node whose removal results in two or more disconnected components, each of which has no more than $\frac{n}{2}$ nodes in it. A tree has either a unique $\frac{n}{2}$-separator or two adjacent $\frac{n}{2}$-separators[8].

The generic leader election algorithm can be viewed as consisting of two separate phases. In the first phase each node i determines, for each $j \in N(i)$, the particular distance property for the node i in the component of $G - j$ that contains i. In the second phase each node determines if it is the one node (or if it and a neighbor of its are the two nodes) in the tree with the desired property. The "output" of the algorithm is that exactly one node will have designated itself as the leader, and all other nodes will know which neighbor of theirs is closer to the leader than they are.

In the following two subsections we describe and prove correct the two phases for a self-stabilizing algorithm that finds an $\frac{n}{2}$-separator of a tree. Note that for a tree, a $\frac{n}{2}$-separator is also a median. Thus, as presented the algorithm solves the median-finding problem. In the third subsection we discuss how to modify the rules presented here for a self-stabilizing center-finding tree algorithm. The extension to finding a root with maximum minimum distance to a leaf is straight-forward.

3.1 Phase one – determining distances from leaves

For this presentation, the distance-from-the-leaves property is the size of the largest subtree. To that end, each node i maintains an array $size_i$ of integer variables. The array contains one value $size_i(j)$ for each $j \in N(i)$. Once the system stabilizes, $size_i(j)$ will contain the number of nodes in the connected component of $G - j$ containing i. Note that only the local variable $size_i(j)$ in node i will be accessed by node $j \in N(i)$, and thus, as is assumed in the self-stabilizing paradigm, no node needs to have knowledge of the existence of nodes that are a distance of two or more from it.

The algorithm described by the rule R1 below runs on each node of the network. We will later show that once the network has stabilized, each node i can determine the number of nodes in the entire network by computing $size_i(j) + size_j(i)$ for any neighbor $j \in N(i)$. Each node interprets the rules by substituting itself in place of i.

R1: **if** $(\exists j \in N(i)$ such that $size_i(j) \neq 1 + \sum_{k \in N(i)-\{j\}} size_k(i))$
then $size_i(j) \leftarrow 1 + \sum_{k \in N(i)-\{j\}} size_k(i))$

Note that if i is a leaf, then $size_i(j)$ will be set to 1 by R1.

Let $v_i(j)$ be the number of nodes in the component of $G - j$ that contains i and let $c_i(j)$ be the number of times that the value of $size_i(j)$ changes. In the following sequence of lemmas we will show that Algorithm R1 stabilizes with $size_i(j) = v_i(j)$ and it does so in a total of at most $n(n-1)$ moves.

Lemma 3.1 *Algorithm R1 stabilizes*

Proof. Consider any sequence of updates $R_1, R_2, \ldots, R_k$ using R1 on a consecutive sequence of nodes $p_1, p_2, \ldots, p_k, p_{k+1}$ such that R_i, $1 < i \leq k$, is the first update of $size_{p_i}(p_{i+1})$ that makes direct use of the value of $size_{p_{i-1}}(p_i)$. The final node p_{k+1}

is used to indicate that the last value updated is $size_{p_k}(p_{k+1})$. The initial move can be arbitrary.

We first show that $p_i \neq p_j$ for $i \neq j$ implying that $k \leq n$. To see this note that by the construction of R1 we cannot have the case where $p_i = p_{i+1}$ or where $p_i = p_{i+2}$. The first observation is obvious from the definition of R1 while the last observation follows from the fact, shown in Figure 1, that $size_i(j)$ is only influenced by values $size_q(i)$, $q \neq j$ and only influences values $size_j(r)$, $r \neq i$. It follows that since $p_{i+1} \in N(i)$ a pair of nodes p_i, p_j where $p_i = p_j$, $j > i+1$, would imply the existence of a cycle in the graph, but this is not possible since G is a tree. Thus we have $k \leq n$.

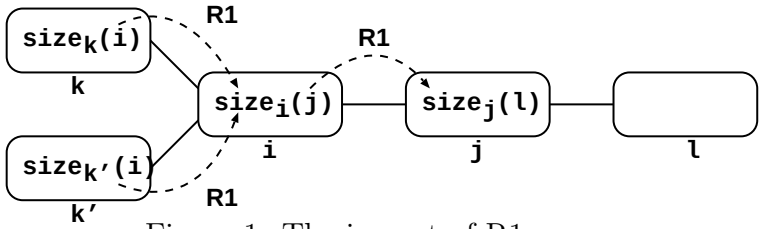

Figure 1: The impact of R1 moves

We now proceed to show that the set of all moves is finite. Consider the set of all maximal sequences as described above. This set contains all the moves made by R1. In a tree the path between two nodes is unique and it follows that there can at most be n^2 such sequences where the order of the nodes is distinct. Thus the only way that the number of moves can be unbounded is if the same sequence appears more than once but using different input values.

To see that this is not the case note that the first move of any maximal sequence must be completely based on the systems initial values. This implies that if R and R' are two maximal sequences such that $p_i = p'_i$ then the initial move for both sequences must be identical. It now follows by induction that R and R' must consist of the same moves since the ith move is unique once the $i-1$th move has been specified. ■

Lemma 3.2 *When Algorithm R1 has stabilized $c_i(j) \leq v_i(j)$.*

Proof. The proof is by induction on the magnitude of $v_i(j)$. The base case is for $v_i(j) = 1$. Then node i must be a leaf in G. If $size_i(j)$ is initially $\neq 1$ the predicate for rule R1 at node i will remain true until R1 is applied. Once $size_i(j) = 1$ (either because that was its initial value or because R1 was applied), the predicate for R1 at node i will remain false and the value of $size_i(j)$ will not change. Thus the result holds true for the base case.

Assume that the result is true for $v_k(l) < r$ and that $v_i(j) = r > 1$. Let $N(i) = \{j, t_1, t_2, \ldots, t_p\}$. Note that since $v_i(j) > 1$ we must have $p \geq 1$. Then $c_i(j) \leq 1 + \sum_{q=1}^{p} c_{t_q}(i)$. This follows since R1 can be applied once initially and then once after each change to any $size_{t_q}(i)$, $1 \leq q \leq p$. The result follows by applying the induction hypothesis and noting that $v_i(j) = 1 + \sum_{q=1}^{p} v_{t_q}(i)$. ■

Lemma 3.3 *When Algorithm R1 has stabilized $size_i(j) = v_i(j)$.*

Proof. The proof is similar to that of Lemma 3.2 and is therefore omitted. ■

Lemma 3.4 *R1 is applied at most $n(n-1)$ times.*

Proof. Since, for any edge (i,j), $v_i(j) + v_j(i) = n$, it follows from Lemma 3.2 that the total number of times that $size_i(j)$ and $size_j(i)$ change is at most n. Since there are $n-1$ edges in G the result follows. ∎

Based on Lemmas 3.1-3.4 we can now conclude:

Theorem 3.5 *For any given tree network, the distributed algorithm R1 stabilizes in no more than $n(n-1)$ moves with $size_i(j) = v_i(j)$ for every pair of adjacent nodes i and j.*

Lemma 3.6 *The bound of $n(n-1)$ moves for R1 is tight.*

Proof. Let G be a path with nodes numbered $1, 2, \ldots, n$. Then the use of R1 can either be on the path $size_1(2), size_2(3), \ldots, size_{n-1}(n)$ or on the path $size_n(n-1), size_{n-1}(n-1), \ldots, size_2(1)$. Consider the first path. Assume that all the initial values are incorrect and that R1 is applied in increasing sequence to $size_i(i+1), size_{i+1}(i+2), \ldots, size_{n-1}(n)$ before it is applied to $size_j(j+1)$ for $j < i$. Then $size_i(i+1)$ will be updated i times before the algorithm stabilizes. Summing this over the whole path gives a total of $(n-1)n/2$ moves. The result now follows since there are two paths. ∎

3.2 Phase two – rooting the tree

The algorithm for rooting the tree is based on each node determining its position relative to a $\frac{n}{2}$-separator in G. To accomplish this, rule R1 (defined in the previous subsection) is used so that "first" every node will know the size of the entire tree. A node i will make the "subsequent" moves of determining its position relative to an $\frac{n}{2}$-separator of the tree only when, from its local perspective, it believes it knows the correct size of the tree. The following predicate is evaluated for this purpose:

$$sizeCorrect_i = (\forall j \in N(i),\ size_i(j) = 1 + \textstyle\sum_{k \in N(i)-\{j\}} size_k(i))$$

Note that when $sizeCorrect_i$ is true rule R1 cannot be applied at node i. The following result shows how a node i can determine the number of nodes in the graph once $sizeCorrect_i$ evaluates to true.

Lemma 3.7 *If $sizeCorrect_i$ is true then $size_i(j) + size_j(i) = size_i(k) + size_k(i)$ for all pairs of nodes $j, k \in N(i)$.*

Proof. This follows since for $j, k \in N(i)$:

$$\begin{aligned} size_i(j) + size_j(i) &= \left(1 + \sum_{q \in N(i)-\{j\}} size_q(i)\right) + size_j(i) \\ &= 1 + \sum_{q \in N(i)} size_q(i) \\ &= \left(1 + \sum_{q \in N(i)-\{k\}} size_q(i)\right) + size_k(i) \\ &= size_i(k) + size_k(i). \end{aligned}$$

∎

Thus when node i stabilizes locally it can calculate the number of nodes it assumes that the graph contains as $n_i = size_i(j) + size_j(i)$ for any $j \in N(i)$. Note that Lemma 3.7 implicitly proves that when R1 has globally stabilized $n_i = n$ for each node i. In this case it is straightforward for node i to determine if it is an $\frac{n}{2}$-separator and if this is not the case to determine its position relative to the separator simply by locating its neighbor j with the largest $size_j(i)$ value.

In addition to the array $size_i$ of integer variables, each node also maintains a parent pointer p_i. When the algorithm terminates the value of p_r for the root node r will be r, while the value of p_i for each node $i \neq r$ will be the neighbor of i that is closest to r.

The algorithm is given by rule R1 together with rules R2–R5 bellow. The R2–R5 predicates all require that $sizeCorrect_i$ be true; thus they can be applied only if R1 cannot be applied. The purpose of these rules are as follows. R2 is used to identify the $\frac{n}{2}$-separator if a unique one exists, and to make the unique separator be the root. R3 is used by nodes that are not $\frac{n}{2}$-separators to set their pointer to their closest-to-the-separator neighbor. R4 and R5 are used in the case where there are two $\frac{n}{2}$-separators. R4 selects as the root the $\frac{n}{2}$-separator with higher unique ID, while R5 sets the pointer of the $\frac{n}{2}$-separator with lower unique ID to point to its $\frac{n}{2}$-separator neighbor. Each node interprets the rules by substituting itself in place of i. The value $size_i(j) + size_j(i)$ for an arbitrary $j \in N(i)$ is used for n_i.

R2: **if** $(sizeCorrect_i)$
and $(\forall j \in N(i)\ size_j(i) < n_i/2)$
and $(p_i \neq i)$
then $(p_i \leftarrow i)$

R3: **if** $(sizeCorrect_i)$
and $(\exists j \in N(i)$ such that $size_j(i) > n_i/2)$
and $(p_i \neq j)$
then $(p_i \leftarrow j)$

R4: **if** $(sizeCorrect_i)$
and $(\exists j \in N(i)$ such that $size_j(i) = n_i/2)$
and $(ID_i > ID_j)$
and $(p_i \neq i)$
then $(p_i \leftarrow i)$

R5: **if** $(sizeCorrect_i)$
and $(\exists j \in N(i)$ such that $size_j(i) = n_i/2)$
and $(ID_i < ID_j)$
and $(p_i \neq j)$
then $(p_i \leftarrow j)$

Lemma 3.8 *For any given tree network, the distributed algorithm R1 – R5 stabilizes in no more than* $2n^2 - n$ *moves.*

Proof. Note first that by Lemma 3.6 rule R1 is applied at most $n(n-1)$ times. Furthermore, a node will apply no more than one of rules R2 through R5 after each application of rule R1 and before rule R1 is applied again. Thus, rules R2 through R5 will be applied at most once initially for each node, and then once again after each application of rule R1. The result follows. ∎

Lemma 3.9 *Once the distributed algorithm R1 – R5 has stabilized on a tree network, the pointer values define a rooted tree with an $\frac{n}{2}$-separator as the root.*

Proof. The predicates and local variables set by rule R1 are not impacted by application of rules R2 through R5. Thus, by Theorem 3.5 rule R1 will stabilize with correct values for each $size_i(j)$.

Consider now the pointer values after R1 – R5 has stabilized. Note that every node i that is not an $\frac{n}{2}$-separator will have exactly one neighbor $j \in N(i)$ such that $size_j(i) > n/2$, and will not have any neighbors with $size_j(i) = n/2$. Thus, after rule R1 has stabilized, these nodes may apply rule R3, and will never apply rules R2, R4, and R5. Whether they apply rule R3 or not, p_i will point to the single neighbor with $size_j(i) > n/2$. It is obvious that this component must contain all $\frac{n}{2}$-separators. Thus, these nodes correctly point towards the neighbor whose subtree contains the $\frac{n}{2}$-separator root.

In the case where there is a unique $\frac{n}{2}$-separator, there is no node with $size_j(i) = n/2$ and the separator node i has $size_j(i) < n/2$ for all $j \in N(i)$. Thus, the unique separator may apply rule R2, but will never apply any of rules R3 through R5. Whether it applies rule R2 or not, p_i will point to i designating i as the root. This, together with the fact that all other nodes in the network are not $\frac{n}{2}$-separators, gives the desired result when there is a unique $\frac{n}{2}$-separator.

In the case where there are two adjacent $\frac{n}{2}$-separators k and q, $size_k(q) = n/2$ and $size_q(k) = n/2$. Moreover, no node i in the network can have $size_j(i) < n/2$ for all $j \in N(i)$. Thus, the separators cannot apply rules R2 or R3, and all other nodes in the network can apply only rule R3. As argued above, the non-separator nodes will correctly set their pointers to point towards the separators. Without loss of generality, let q be the separator with larger ID and k be the other separator. Clearly node q may apply rule R4, and will never apply rule R5. Analogously, node k may apply rule R5, and will never apply rule R4. Regardless of whether or not rules R4 and R5 are applied here, when the algorithm stabilizes, we will have $p_q = q$ and $p_k = q$. This gives the desired result for the case when there are two $\frac{n}{2}$-separators. ∎

Thus we can conclude:

Theorem 3.10 *For any given tree network, the distributed algorithm R1–R5 stabilizes in no more than $2n^2 - n$ moves with the values of p_i for all nodes i defining a rooted tree with an $\frac{n}{2}$-separator as the root.*

3.3 Other criteria for leaders

In this subsection we outline a generic version of our rooting algorithm and then briefly discuss how the $\frac{n}{2}$-separator algorithm can be modified to find the center of a tree.

In the generic version of the rooting algorithm we maintain, at each node i, an array $dist_i$ rather than the array $size_i$. The value $dist_i(j)$ for each $j \in N(i)$ will contain the value of the distance-from-the-leaves property in the connected component of $G - j$ containing i, once the system has stabilized. Let the function $dfl(\cup_{k \in N(i)-\{j\}} dist_k(i))$ be one that calculates the value of the distance-from-the-leaves property for a node i based on the value of the distance-from-the-leaves property of all "children" neighbors (i.e., all neighbors $k \neq j$). Then rule R1 can be re-written as follows.

R1: **if** $(\exists j \in N(i)$ such that $dist_i(j) \neq dfl(\cup_{k \in N(i)-\{j\}} dist_k(i))$
then $dist_i(j) \leftarrow dfl(\cup_{k \in N(i)-\{j\}} dist_k(i))$

It is easy to see that the $\frac{n}{2}$-separator algorithm given in Subsection 3.1 is the generic algorithm instantiated with $dfl(\cup_{k \in N(i)-\{j\}} dist_k(i)) = 1 + \sum_{k \in N(i)-\{j\}} dist_k(i)$ for both leaves and internal nodes. Furthermore, the algorithm given in [5] for finding the median of a tree is just this with the exception that the algorithm in [5] calculates only one dfl value for the currently assumed parent of node i, rather than calculating a dfl value for every possible parent. Since our algorithm stabilizes with each node having full knowledge of which node is its parent, our algorithm clearly calculates also the median of a tree. It is worth highlighting the difference between the two median-finding algorithms: our algorithm maintains more values than does the algorithm in [5], but does so in only $O(n^2)$ moves as compared to the $O(n^3 + n^2 \cdot c_h)$ moves required by the algorithm in [5].

In a similar fashion we can utilize the criteria in [5] that finds the center of a tree inorder to instantiate an $O(n^2)$ self-stabilizing algorithm. Here the parameter function $dfl(\cup_{k \in N(i)-\{j\}} dist_k(i)) = 1 + \max_{k \in N(i)-\{j\}} \{dist_k(i)\}$ for both leaves and internal nodes[3] results in our rule R1 giving a similar center finding algorithm to that given in [5]. The difference is again that our algorithm calculates a dfl for every possible parent, but does so in fewer moves in the worst case.

The rooting algorithms in [5] contain only their version of rule R1. They prove that then the node (or two nodes) that is (are) the leader(s), either median or center, can determine its (their) leader-status by comparing its distance-from-the-leaves property with that of all of its (their) neighbors. We have gone further in Subsection 3.2 by explicitly accomplishing this determination of who the leader is as well as setting pointers for the corresponding rooted tree with rules R2 through R5. These rules can be generalized in the same way that we have generalized rule R1 above by defining generic parameter functions for determining whether or not a node is the leader and substituting those generic parameter functions in for the second condition of each of rules R2 through R5. In the interest of space, we omit these generalizations here.

4 A Generic Bottom-Up Algorithm

Many graph problems can be solved efficiently on trees in a bottom-up fashion. The main idea is to first root the tree at some node r, and then to propagate computation from the leaf nodes towards r as follows. Let $child(i)$ be the set of node i's children in the rooted tree. We assume that a function $f(j)$ has been computed for each $j \in child(i)$. Then $f(i) = g(\cup_{j \in child(i)} f(j))$ for some function g. If i is a leaf then $g() = c$ where c is an appropriate constant. If g can be computed in $O(1)$ time then the sequential time of this algorithm is $O(n)$. The solution is given by the union of all f values.

There exists several examples of self-stabilizing algorithms for solving such problems. The broad class of algorithms in [7] solve these problems in $O(n^3 + n^2 c_h)$ moves, where c_h is the maximum initialized value of a variable. In [4] a self-stabilizing algorithm is given for finding a maximum matching in a tree. Their algorithm requires $O(n^2 \cdot h(n))$ moves, where $h(n)$ moves are needed to root the tree. Thus, combined

[3] This assumes the function $\max_{k \in N(i)-\{j\}} dist_k(i)$ evaluates to zero when $N(i) = \{j\}$.

with our rooting algorithm their algorithm uses $O(n^4)$ moves. In this section we will show how all of these problems can be solved by a self-stabilizing algorithm in only $O(n^2)$ time.

The main idea behind our algorithm is to simultaneously solve the problem with each possible node as the root, storing the results for each node i in an array f_i. As with the $size_i$ array, the value of $f_i(j)$ for $j \in N(i)$ contains the desired result for node i, assuming j is the parent of i in a rooted tree. Independently and simultaneously we run both the bottom-up algorithm to calculate the f_i values and also an instantiated generic rooting algorithm. Combined, the two algorithms will stabilize in $O(n^2)$ time. When the combined algorithm stabilizes each node knows its relative position to the root and can use its f values together with the f values of its neighbors to determine which of its f values is its solution.

We are now ready to begin describing the new algorithm. Assume that G is rooted and that j is the parent of node i. We first observe that the value of $f(i)$ is independent of which node is the root of G as long as it is situated in the component of $G - i$ that contains j.

Initially G is not rooted, but we know that for any edge (i, j) we must either have $p_i = j$ or $p_j = i$. Thus if for each edge (i, j) we calculate both $f(i)$ under the assumption that $p_i = j$ and similarly $f(j)$ assuming that $p_j = i$ we will, once the tree is rooted, have all the f values needed to compute a global solution. Note that for the root we must set $f(i) = g(\cup_{k \in N(i)} f_k(i))$.

We define for each edge $(i, j) \in E$ variables $f_i(j)$ and $f_j(i)$ associated with node i and j respectively. We also define a variable $f_i(i)$ for each node which contains node i's final f value. Our algorithm consists of rules R1 through R5 of the $\frac{n}{2}$-separator algorithm combined with the following three rules.

R6: **if** $(\exists j \in N(i)$ such that $f_i(j) \neq g(\cup_{k \in N(i)-\{j\}} f_k(i))$
then $f_i(j) \leftarrow g(\cup_{k \in N(i)-\{j\}} f_k(i))$

R7: **if** $(p_i = i)$
and $f_i(i) \neq g(\cup_{j \in N(i)} f_j(i))$
then $(f_i(i) \leftarrow g(\cup_{j \in N(i)} f_j(i))$

R8: **if** $(p_i \neq i)$
and $(f_i(i) \neq f_i(p_i))$
then $(f_i(i) \leftarrow f_i(p_i))$

Note that in rule R6 we assume that a node can detect if it is a leaf and in this case we define $g() = c$ for some appropriate constant c.

Theorem 4.1 *Algorithm R1 – R8 stabilizes after $O(n^2)$ moves.*

Proof. Note first that R6 is a generalization of R1 with the *dfl* function replaced by g. Thus, the number of times an R6 move is made is the same as R1. Rules R7 and R8 may fire once initially and then at most once after each change in p_i or some neighboring f value. ¿From the above discussion and Theorem 3.10 it follows that the total number of rule R7 and R8 moves is $O(n^2)$. ∎

Theorem 4.2 *Once the distributed algorithm R1 – R8 has stabilized on a tree network, the values of $f_i(i)$ solve the associated graph problem.*

Proof. The correctnes of the algorithm follows from the fact that R6 behaves in the same way as R1. Thus after R1 through R6 have stabilized only one of rules R7 and R8 may fire once for each node to set $f_i(i)$ to its correct value. ∎

As an example of how this algorithm can be used to solve a particular problem, we consider the problem of finding a maximum independent set in a tree. A sequential algorithm to solve this was given in [14]. The algorithm effectively roots the tree at its center and then processes the nodes starting from the leaves, working towards the root. Each node is included in the independent set if none of its children are in the set. To convert this to a self-stabilizing algorithm, we simply consider f_i to be the appropriate boolean value, defining the algorithm with the function set $g() = \text{TRUE}$ and $g(\cup_{j \in set(i)} f_j(i)) = \wedge_{j \in set(i)}(\neg f_j(i))$ where $set(i) = child(i)$ for non-root nodes and $set(i) = N(i)$ for the root. The correctness of this algorithm follows directly from the correctness of the sequential algorithm.

5 Concluding Remarks

We have defined a generic self-stabilizing leader election algorithm that can be instantiated with any distance-from-the-leaves property defining a unique leader (or one of two if each can identify the other) in $O(n^2)$ moves. We showed how to instantiate the generic leader election algorithm to find a center, a median and an $\frac{n}{2}$-separator of a tree, and then to root the corresponding tree.

In Section 4 we showed how to use our $O(n^2)$ leader election algorithms together with a generic self-stabilizing bottom-up algorithm to solve numerous other problems. This last algorithm is a mapping from any single pass bottom-up sequential algorithm to a self-stabilizing algorithm that solves the same problem in $O(n^2)$ moves.

The main idea behind our more efficient algorithms is to set up the rules so that updates will propagate along *directed* acyclic paths in an undirected tree. In this way one avoids cycles in the updates and thus obtains fast convergence.

All of the previously-published self-stabilizing tree algorithms mentioned in Section 1 have the characteristic that they locally compute a required value at each node based on a current view of which neighbor is the node's parent. Each time the parent changes, as it does frequently up until stabilization of the rooting algorithm, the value is recomputed. It is at this point that information may in fact be lost. If later the local view of the parent is switched back, then the required value must be recomputed even if nothing has changed other than the view of who the parent is. The algorithms presented in this paper avoid this unnecessary re-computation of values by locally maintaining values for each possible parent (e.g., $size_i(j)$ for *all* $j \in N(i)$). Each value is computed in exactly the same way that it is computed in a sequential algorithm to solve the same problem in a directed acyclic fashion. In the self-stabilizing paradigm, however, we compute values based on all possible rooted tree views. Once the actual root is known, each node can easily select its correct required value (e.g., select the j for which $size_j(i)$ is maximum).

The use of an array of local variables for each node could cause a problem in the self-stabilizing paradigm because access to the entire array by a neighbor might constitute the neighbor having to know of the existence of nodes that are not its neighbors (i.e., nodes that are a distance two away from it). This is not a problem for our algorithms since using our algorithms each neighbor accesses exactly one of

the values in the array (e.g., neighbor j will access $size_i(j)$, but will not access any other values in the $size_i$ array).

Our algorithms assumed the existence of a static unique identifier i for each node. Note, however, that in the case where it is not necessary to distinguish between two possible adjacent roots, our algorithms can easily be adapted to work without unique identifiers, as was done in [5]. In this case, we would simply change the predicate for rule R3 in the generic rooting algorithm to check for all possible roots (e.g., $size_j(i) \leq n_i/2$), rather than a unique root. Rules R4 and R5 would not be needed then.

Finally, note that as with other previously published self-stabilizing tree algorithms our algorithms work as well for dynamically changing tree topologies, as long as there is enough time between changes to the topology to allow the system to stabilize.

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