A Space-Efficient Algorithm for Finding Strongly Connected Components

David J. Pearce
School of Engineering and Computer Science
Victoria University, New Zealand
david.pearce@ecs.vuw.ac.nz

Abstract

Tarjan’s algorithm for finding the strongly connected components of a directed graph is widely used and acclaimed. His original algorithm required at most $v(2 + 5w)$ bits of storage, where $w$ is the machine’s word size, whilst Nuutila and Soisalon-Soininen reduced this to $v(1 + 4w)$. Many real world applications routinely operate on very large graphs where the storage requirements of such algorithms is a concern. We present a novel improvement on Tarjan’s algorithm which reduces the space requirements to $v(1 + 3w)$ bits in the worst case. Furthermore, our algorithm has been independently integrated into the widely-used SciPy library for scientific computing.

Keywords: Graph Algorithms, Strongly Connected Components, Depth-First Search.

1. Introduction

For a directed graph $D = (V, E)$, a Strongly Connected Component (SCC) is a maximal induced subgraph $S = (V_S, E_S)$ where, for every $x, y \in V_S$, there is a path from $x$ to $y$ (and vice-versa). Tarjan presented a now well-established algorithm for computing the strongly connected components of a digraph in time $\Theta(v + e)$ [14]. In the worst case, this needs $v(2 + 5w)$ bits of storage, where $w$ is the machine’s word size. Nuutila and Soisalon-Soininen reduced this to $v(1 + 4w)$ [10]. In this paper, we present for the first time an algorithm requiring only $v(1 + 3w)$ bits in the worst case. Furthermore, this algorithm has been independently integrated into the widely-used SciPy library for scientific computing specifically because of its ability to handle larger graphs in practice [13].

Tarjan’s algorithm has found numerous uses in the literature, often as a subcomponent of larger algorithms, such as those for transitive closure [9], compiler optimisation [5], program analysis [1, 11] and for bisimulation equivalence [2] to name but a few. Of particular relevance is its use in model checking [7, 12], where the algorithm’s storage requirements are a critical factor limiting the number of states which can be explored [8, 4].

2. Depth-First Search

Algorithm 1 presents a well-known procedure for traversing digraphs, known as Depth First Search (DFS). We say that an edge $v \rightarrow w$ is traversed if visit($w$) is called from visit($v$) and that the value of index on entry to visit($v$) is the visitation index of $v$. Furthermore, when visit($w$) returns we say the algorithm is backtracking from $w$ to $v$.

The algorithm works by traversing along some branch until a leaf or a previously visited vertex is reached; then, it backtrackst to the most recently visited vertex with an unexplored edge and proceeds along this; when there is no such vertex, one is chosen from the set of unvisited vertices and this continues until the whole digraph has been
Algorithm 1 DFS(V,E)

1: index = 0
2: for all v ∈ V do visited[v] = false
3: for all v ∈ V do
4:     if ¬visited[v] then visit(v)
5: procedure visit(v)
6:     visited[v] = true; index = index + 1
7:     for all v → w ∈ E do
8:         if ¬visited[w] then visit(w)

Figure 1: Illustrating three possible traversal forests for the same graph. The key is as follows: vertices are subscripted with their visitation index; dotted lines separate traversal trees; dashed edges indicate those edges not traversed; finally, bold vertices are tree roots.

explored. Such a traversal always corresponds to a series of disjoint trees, called traversal trees, which span the digraph. Taken together, these are referred to as a traversal forest. Figure 1 provides some example traversal forests.

Formally, $F = (I, T_0, \ldots, T_n)$ denotes a traversal forest over a digraph $D = (V, E)$. Here, $I$ maps every vertex to its visitation index and each $T_i$ is a traversal tree given by $(r, V_{T_i} \subseteq V, E_{T_i} \subseteq E)$, where $r$ is its root. It is easy to see that, if visit$(x)$ is called from the outer loop, then $x$ is the root of a traversal tree. For a traversal forest $F$, those edges making up its traversal trees are tree-edges, whilst the remainder are non-tree edges. Non-tree edges can be further subdivided into forward-, back- and cross-edges:

Definition 1. For a directed graph, $D = (V, E)$, a node $x$ reaches a node $y$, written $x \sim_D y$, if $x = y$ or $\exists z. [x \rightarrow z \in E \land z \sim_D y]$. The $D$ is often omitted from $\sim_D$, when it is clear from the context.

Definition 2. For a digraph $D = (V, E)$, an edge $x \rightarrow y \in E$ is a forward-edge, with respect to some tree $T = (r, V_T, E_T)$, if $x \rightarrow y \notin E_T \land x \neq y \land x \sim_T^y$.

Definition 3. For a digraph $D = (V, E)$, an edge $x \rightarrow y \in E$ is a back-edge, with respect to some tree $T = (r, V_T, E_T)$, if $x \rightarrow y \notin E_T \land y \sim_T^x$.

Cross-edges constitute those which are neither forward- nor back-edges. A few simple observations can be made about these edge types: firstly, if $x \rightarrow y$ is a forward-edge, then $I(x) < I(y)$; secondly, cross-edges may be intra-tree (i.e. connecting vertices in the same tree) or inter-tree; thirdly, for a back-edge $x \rightarrow y$ (note, Tarjan called these fronds), it holds that $I(x) \geq I(y)$ and all vertices on a path from $y$ to $x$ are part of the same strongly connected component. In fact, it can also be shown that $I(x) > I(y)$ always holds for a cross-edge $x \rightarrow y$ (see Lemma 1, page 10).
Two fundamental concepts behind efficient algorithms for this problem are the local root (note, Tarjan called these LOWLINK values) and component root: the local root of \( v \) is the vertex with the lowest visitation index of any in the same component reachable by a path from \( v \) involving at most one back-edge; the root of a component is the member with lowest visitation index. The significance of local roots is that they can be computed efficiently and that, if \( r \) is the local root of \( v \), then \( r = v \) iff \( v \) is the root of a component (see Lemma 3, page 10). Thus, local roots can be used to identify component roots.

Another important topic, at least from the point of view of this paper, is the additional storage requirements of Algorithm 1 over that of the underlying graph data structure. Certainly, \( v \) bits are needed for \( \text{visited}[:], \) where \( v = |V| \). Furthermore, each activation record for \( \text{visit}() \) holds the value of \( v \), as well as the current position in \( v \)’s out-edge set. The latter is needed to ensure each edge is iterated at most once. Since no vertex can be visited twice, the call-stack can be at most \( v \) vertices deep and, hence, consumes at most \( 2vw \) bits of storage, where \( w \) is the machine’s word size. Note, while each activation record may hold more items in practice (e.g. the return address), these can be avoided by using a non-recursive implementation (see §4). Thus, Algorithm 1 requires at most \( v(1 + 2w) \) bits of storage. Note, we have ignored index here, since we are concerned only with storage proportional to \(|V|\).

3. Improved Algorithm for Finding Strongly Connected Components

Tarjan’s algorithm and its variants are based upon Algorithm 1 and the ideas laid out in the previous section. Given a directed graph \( D = (V, E) \), the objective is to compute an array mapping vertices to component identifiers, such that \( v \) and \( w \) map to the same identifier iff they are members of the same component. Tarjan was the first to show this could be done in \( \Theta(v + e) \) time, where \( v = |V| \) and \( e = |E| \). Tarjan’s algorithm uses the backtracking phase of Depth-First Search to explicitly compute the local root of each vertex. An array of size \( |V| \), mapping each vertex to its local root, stores this information. Another array of size \( |V| \) is needed to map vertices to their visitation index. Thus, these two arrays consume \( 2vw \) bits of storage between them.

The key insight behind our improvement is that these arrays can, in fact, be combined into one. This array, \( \text{rindex}[:], \) maps each vertex to the visitation index of its local root. The outline of our new algorithm, PEA_FIND_SCC1, is as follows: on entry to \( \text{visit}(v) \), \( \text{rindex}[v] \) is assigned the visitation index of \( v \); then, after each successor \( w \) is visited, \( \text{rindex}[v] = \min(\text{rindex}[v], \text{rindex}[w]) \). Figure 2 illustrates this. The algorithm determines which vertices are in the same component (e.g. \( B, C, D, E, G \) in Figure 2) in the following way: if, upon completion of \( \text{visit}(v) \), the local root of \( v \) is not \( v \), then push \( v \) onto a stack; otherwise, \( v \) is the root of a component and its members are popped off the stack and assigned its unique component identifier. In Tarjan’s original algorithm, the local root of a vertex was maintained explicitly and, hence, it was straightforward to determine whether a vertex was the root of some component or not. In our improved algorithm, this information is not available and, hence, we need another way of determining this. In fact, it is easy enough to see that the local root of a vertex \( v \) is \( v \) iff \( \text{rindex}[v] \) has not changed after visiting any successor.

Pseudo-code for the entire procedure is given in Algorithm 2 and there are several points to make: firstly, \( \text{root} \) is used (as discussed above) to detect whether \( \text{rindex}[v] \) has changed whilst visiting \( v \) (hence, whether \( v \) is a component
Figure 2: Illustrating the \textit{rindex} computation. As before, vertices are subscripted with visitation index and dashed edges are those not traversed.

The left diagram illustrates \textit{rindex}[\cdot] after the path $A \leadsto E$ has been traversed. On entry to visit($E$), \textit{rindex}[$E$] = 4 held, but was changed to $\min(4, \textit{rindex}[^C]) = 2$ because of the edge $E \rightarrow C$. In the middle diagram, visit($E$) and visit($F$) have completed (hence, the algorithm is backtracking) and \textit{rindex}[$D$] is $\min(3, \textit{rindex}[E], \textit{rindex}[F]) = 2$. Likewise, \textit{rindex}[$G$] = $\min(6, \textit{rindex}[B]) = 1$ in the right diagram because of $G \rightarrow B$. At this point, the algorithm will backtrack to $A$ before terminating, setting \textit{rindex}[C] = 1, \textit{rindex}[B] = 1 and \textit{rindex}[A] = 0 as it goes.

Figure 3: Illustrating why the \textit{inComponent}[$\cdot$] array is needed. As before, vertices are subscripted with their visitation index; dashed edges indicate those not traversed; finally, \textit{inComponent}[v] = true is indicated by a dashed border. In the leftmost diagram, we see that the traversal started from $B$ and that $D$ has already been assigned to its own component (hence, \textit{inComponent}[D] = true). In the middle diagram, the algorithm is now exploring vertices reachable from $A$, having assigned $B, C, D$ and $E$ to their own components. A subtle point is that, on entry to visit($A$), \textit{rindex}[$B] < \textit{rindex}[A]$ held (since $A \rightarrow B$ is a cross-edge). Thus, if \textit{inComponent}[$\cdot$] information was not used on Line 11 to ignore successors already assigned to a component, the algorithm would have incorrectly concluded \textit{rindex}[A] = $\min(\textit{rindex}[A], \textit{rindex}[B]) = 0$. In the final diagram, \textit{inComponent}[I] = false on entry to visit($H$) because a vertex is not assigned to a component until its component root has completed.
Algorithm 2 PEA_FIND_SCC1(V,E)

1: for all \(v \in V\) do \(\text{visited}[v] = \text{false}\)
2: \(S = \emptyset; index = 0; c = 0\)
3: for all \(v \in V\) do
4: \(\text{if } \neg\text{visited}[v] \text{ then } \text{visit}(v)\)
5: return \(rindex\)

procedure \(\text{visit}(v)\)
6: \(\text{root} = \text{true} ; \text{visited}[v] = \text{true}\)  // root is local variable
7: \(rindex[v] = \text{index} ; \text{index} = \text{index} + 1\)
8: \(\text{inComponent}[v] = \text{false}\)
9: for all \(v \rightarrow w \in E \) do
10: \(\text{if } \neg\text{visited}[w] \text{ then } \text{visit}(w)\)
11: \(\text{if } \neg\text{inComponent}[w] \land rindex[w] < rindex[v] \text{ then}\)
12: \(rindex[v] = rindex[w] ; \text{root} = \text{false}\)
13: if \(\text{root} \) then
14: \(\text{inComponent}[v] = \text{true}\)
15: while \(S \neq \emptyset \land rindex[v] \leq rindex[\text{top}(S)]\) do
16: \(w \equiv \text{pop}(S)\)  // \(w\) in SCC with \(v\)
17: \(rindex[w] = c\)
18: \(\text{inComponent}[w] = \text{true}\)
19: \(rindex[v] = c\)
20: \(c = c + 1\)
21: else
22: push\((S, v)\)

root); secondly, \(c\) is used to give members of a component the same component identifier; finally, the \(\text{inComponent}[]\) array is needed for dealing with cross-edges. Figure 3 aims to clarify this latter point.

At first glance, Algorithm 2 appears to require \(v(3+4w)\) bits of storage in the worst-case. This breaks down in the following way: \(v\) bits for \(\text{visited}\); \(vw\) bits for \(\text{rindex}\); \(vw\) bits for \(S\) (since a component may contain all of \(V\)); \(2vw\) bits for the call-stack (as before); finally, \(v\) bits for \(\text{inComponent}\) and \(v\) bits for \(\text{root}\) (since this represents a boolean stack holding at most \(|V|\) elements).

However, a closer examination reveals the following observation: let \(T\) represent the stack of vertices currently being visited (thus, \(T\) is a slice of the call stack); now, if \(v \in T\) then \(v \notin S\) holds and vice-versa (note, we can ignore the brief moment a vertex is on both, since it is at most one at any time). Thus, \(T\) and \(S\) can share the same \(vw\) bits of storage to give a total requirement of \(v(3+3w)\) for Algorithm 2 (although this does require a non-recursive implementation as before — see §4).

**Theorem 1.** Let \(D = (V,E)\) be a directed graph. if Algorithm 2 is applied to \(D\) then, upon termination, \(rindex[v] = rindex[w]\) iff vertices \(v\) and \(w\) are in the same strongly connected component.

**Proof.** Following Tarjan, we prove by induction the computation is correct. Let the induction hypothesis be that, for every vertex \(v\) where \(\text{visit}(v)\) has completed, \(rindex[v]\) and \(\text{inComponent}[v]\) are correct. That is, if \(\text{inComponent}[v] = \text{true}\) then \(rindex[v] = rindex[w]\), for every \(w\) in \(v\)'s component; otherwise, \(\text{inComponent}[v] = \text{false}\) and \(rindex[v]\) holds the visitation index of \(v\)'s local root. Thus, \(k\) is the number of completions of \(\text{visit}()\). For \(k = 1\), \(\text{visit}(x)\) has only completed for some vertex \(x\). If \(x\) has no successors, \(rindex[x]\) was assigned a unique component identifier and \(\text{inComponent}[x] = \text{true}\); otherwise \(rindex[x] = \min\{I(y) \mid x \rightarrow y \in E\}\) and \(\text{inComponent}[x] = \text{false}\). Both are
correct because: a vertex with no successors is its own component; and any \( x \to y \) is a back-edge since \( \text{visit}(y) \) has not completed.

For \( k = n \), we have that \( \text{visit}(\cdot) \) has completed \( n \) times. Let \( x \) be the vertex where \( \text{visit}(x) \) will complete next. Assume that, when Line 13 is reached, \( \text{rindex}[x] \) holds the visitation index of \( x \)'s local root. Then, the algorithm correctly determines whether \( x \) is a component root or not (following Lemma 3, which implies \( \text{rindex}[x] = I(x) \) iff \( x \) is a component root). If not, \( \text{inComponent}[x] = \text{false} \) and \( \text{rindex}[x] \) is unchanged when \( \text{visit}(x) \) completes. If \( x \) is a component root, then the other members of its component are stored consecutively at the top of the stack. This is because otherwise some member \( u \) was incorrectly identified as a component root, or some non-member \( u \) was not identified as a component root (either implies \( \text{rindex}[u] \) was incorrect during \( \text{visit}(u) \) at Line 13). Since the other members are immediately removed from the stack and (including \( x \)) assigned to the same unique component, the induction hypothesis holds.

Now, it remains to show that, on Line 13, \( \text{rindex}[x] \) does hold the visitation index of \( x \)'s local root. Certainly, if \( x \) has no successors then \( \text{rindex}[x] = I(x) \) at this point. For the case that \( x \) has one or more successors then \( \text{rindex}[x] = \min\{\text{rindex}[y] \mid x \to y \in E \land \text{inComponent}[y] = \text{false}\} \) at this point. To see why this is correct, consider the two cases for a successor \( y \):

(i) \( \text{inComponent}[y] = \text{true} \). Let \( z \) be \( y \)'s component root. It follows that \( \text{visit}(z) \) has completed and was assigned to the same component as \( y \) (otherwise some \( u \), where \( \text{visit}(u) \) has completed, was identified as \( y \)'s component root, implying \( \text{rindex}[u] \) is incorrect). Now, \( x \) cannot be in the same component as \( y \), as this implies \( z \sim x \) (by Lemma 2) and, hence, that \( \text{visit}(z) \) had not completed. Thus, the local root of \( y \) cannot be the local root of \( x \) and, hence, \( x \to y \) should be ignored when computing \( \text{rindex}[x] \).

(ii) \( \text{inComponent}[y] = \text{false} \). Let \( z \) be \( y \)'s component root. By a similar argument to above, \( \text{visit}(z) \) has not completed and, hence, \( z \sim x \). Therefore, \( x \) is in the same component as \( y \) since \( y \sim z \) and, hence, \( \text{rindex}[y] \) should be considered when computing \( \text{rindex}[x] \).

\( \square \)

4. Further Improvements

In this section, we present three improvements to Algorithm 2 which reduce its storage requirements to \( \nu(1 + 3w) \) by eliminating \( \text{inComponent}[: \cdot] \) and \( \text{visited}[: \cdot] \). To eliminate the \( \text{inComponent}[: \cdot] \) array we use a variation on a technique briefly outlined by Nuutila and Soisalon-Soininen [10]. For \( \text{visited}[: \cdot] \), a simpler technique is possible.

The \( \text{inComponent}[: \cdot] \) array distinguishes vertices which have been assigned to a component and those which have not. This is used on Line 11 in Algorithm 2 to prevent \( \text{rindex}[w] \) being assigned to \( \text{rindex}[v] \) in the case that \( w \) has already been assigned to a component. Thus, if we could ensure that \( \text{rindex}[v] \leq \text{rindex}[w] \) always held in this situation, the check against \( \text{inComponent}[w] \) (hence, the whole array) could be safely removed. When a vertex \( v \) is assigned to a component, \( \text{rindex}[v] \) is assigned a component identifier. Thus, if component identifiers were always greater than other \( \text{rindex}[: \cdot] \) values, the required invariant would hold. This amounts to ensuring that \( \text{index} < c \) always holds (since \( \text{rindex}[: \cdot] \) is initialised from \( \text{index} \)). Therefore, we make several specific changes: firstly, \( c \) is
Algorithm 3 PEA_FIND_SCC2(V,E)

1: for all $v \in V$ do $\begin{array}{l} rindex[v] = 0 \\
2: S = \emptyset ; \text{index} = 1 ; c = |V| - 1 \\
3: \end{array}$
4: for all $v \in V$ do $\begin{array}{l} \text{if } rindex[v] = 0 \text{ then visit}(v) \\
5: \text{return } rindex \\
6: \end{array}$

procedure visit($v$)$\begin{array}{l} \mathbf{root} = \text{true} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \q
and is done in finishedEdge().

5. Related Work

Tarjan’s original algorithm needed $v(2 + 5w)$ bits of storage in the worst case. This differs from our result primarily because (as discussed) separate arrays were needed to store the visitation index and local root of each vertex. In addition, Tarjan’s algorithm could place unnecessary vertices onto the stack $S$. Nuutila and Soisalon-Soininen addressed this latter issue [10]. However, they did not observe that their improvement reduced the storage requirements to $v(2+4w)$ (this corresponds to combining stacks $S$ and $T$, as discussed in Section 3). They also briefly suggested that the $inComponent[\cdot]$ array could be eliminated, although did not provide details. Finally, Gabow devised an algorithm similar to Tarjan’s which (essentially) stored local roots using a stack rather than an array [3]. As such, its worst-case storage requirement is still $v(2 + 5w)$.

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Algorithm 4 PEA\_FIND\_SCC3(V,E)

1: for all \(v \in V\) do \(\text{rindex}[v] = 0\)
2: \(vS = \emptyset\ ; iS = \emptyset\) \(\text{index} = 1\ ; c = |V| - 1\)
3: for all \(v \in V\) do
4: \(\text{if rindex}[v] = 0\) then visit\(v\)
5: return \(\text{rindex}\)

procedure visit\(v\)
6: beginVisiting\(v\)
7: while \(vS \neq \emptyset\) do
8: visitLoop()

procedure visitLoop()
9: \(v = \text{top}(vS)\ ; i = \text{top}(iS)\)
10: while \(i \leq |E(v)|\) do
11: if \(i > 0\) then finishEdge\((v, i - 1)\)
12: if \(i < |E(v)| \land \text{beginEdge}(v, i)\) then return
13: \(i = i + 1\)
14: finishVisiting\(v\)

procedure beginVisiting\(v\)
15: push\((vS, v)\) ; push\((iS, 0)\)
16: \(\text{root}[v] = \text{true} ; \text{rindex}[v] = \text{index} ; \text{index} = \text{index} + 1\)

procedure finishVisiting\(v\)
17: pop\((vS)\) ; pop\((iS)\)
18: if \(\text{root}[v]\) then
19: \(\text{index} = \text{index} - 1\)
20: while \(vS \neq \emptyset\ \land \text{rindex}[v] \leq \text{rindex}[\text{top}(vS)]\) do
21: \(w = \text{pop}(vS)\)
22: \(\text{rindex}[w] = c\)
23: \(\text{index} = \text{index} - 1\)
24: \(\text{rindex}[v] = c\)
25: \(c = c - 1\)
26: else
27: push\((vS, v)\)

procedure beginEdge\((v, k)\)
28: \(w = E(v)[k]\)
29: if \(\text{rindex}[w] == 0\) then
30: pop\((iS)\) ; push\((iS, k + 1)\)
31: beginVisiting\(w)\)
32: return \(\text{true}\)
33: else
34: return \(\text{false}\)

procedure finishEdge\((v, k)\)
35: \(w = E(v)[k]\)
36: if \(\text{rindex}[w] < \text{rindex}[v]\) then \(\text{rindex}[v] = \text{rindex}[w] ; \text{root}[v] = \text{false}\)
Appendix A. Appendix

For completeness, we provide in this Section proofs of several key points first shown by Tarjan [14]:

**Lemma 1.** Let $D = (V, E)$ be a digraph and $F = (I, T_0, \ldots, T_n)$ a traversal forest over $D$. If $x \rightarrow y$ is a cross-edge then $I(x) > I(y)$.

**Proof.** Suppose this were not the case. Then, $I(x) < I(y)$ (note, $x \neq y$ as self-loops are back-edges) and, hence, $x$ was visited before $y$ (recall visitation index is defined in terms of index in Algorithm 1, where it is increased on every visit and never decreased). Thus, when visited ($y$) was invoked, $visited[y] = false$. This gives a contradiction because either visit($x$) invoked visit($y$) (hence $x \rightarrow y$ is a tree-edge) or $\exists z. [x \rightarrow z]$ and visit($z$) invoked visit($y$) (hence, $x \rightarrow y$ is a forward-edge). □

**Lemma 2.** Let $D = (V, E)$ be a digraph and $F = (I, T_0, \ldots, T_n)$ a traversal forest over $D$. If $S = (V_S \subseteq V, E_S \subseteq E)$ is a strongly connected component with root $r$, then $\exists ! T_i \in F. \forall v \in V_s. [r \rightarrow T_i \rightarrow v]$.

**Proof.** Suppose not. Then there exists an edge $v \rightarrow w \notin E_T$, where $v, w \in V_s \land r \rightarrow T_i \rightarrow v \land T_i \rightarrow w$ (otherwise, $w$ is not reachable from $r$ and, hence, cannot be in the same component). It follows that $I(w) < I(v)$, because otherwise visit($v$) would have invoked visit($w$) (which would imply $v \rightarrow w \in E_T$). Since $v \in T_i$, we know that $r \rightarrow T_i u$, for any vertex $u$ where $I(r) \leq I(u) \leq I(v)$ (since all vertices traversed from $r$ are allocated consecutive indices). Thus, $I(w) < I(r)$ (otherwise $r \rightarrow T_i w$) which gives a contradiction since it implies $r$ is not the root of $S$. □

**Lemma 3.** Let $D = (V, E)$ be a digraph, $S = (V_S \subseteq V, E_S \subseteq E)$ a strongly connected component contained and $r_v$ the local root of a vertex $v \in V_S$. Then, $r = v$ iff $v$ is the root of $S$.

**Proof.** Let $r_S$ be the root of $S$. Now, there are two cases to consider:

i) If $v = r_S$ then $r_v = v$. This must hold as $r_v \neq v$ implies $I(r_v) < I(v)$ and, hence, that $v \neq r_S$.

ii) If $r_v = v$ then $v = r_S$. Suppose not. Then, $I(r_S) < I(r_v)$ and, as $S$ is an SCC, $r_v \rightarrow r_S$ must hold. Therefore, there must be some back-edge $w \rightarrow r_S \in E$, where $r_v \rightarrow w \land I(r_S) < I(r_v) < I(w)$ (otherwise, $r_v$ could not reach $r_S$). This is a contradiction as it implies $r_S$ (not $r_v$) is the local root of $v$. □