Chapter 10

Strongly Connected Components and Topological Sort.

10.1 Topological Sort

Definition 10.1.1. (connectivity)

1. Let $G = (V, E)$ be a non-directed graph. A **connected component** of G is a subset $U \subseteq V$ of maximal size in which there exists a path between every two vertices.

2. A non-directed graph G is said to be a **connected** graph if it only has one connected component.

3. Let $G = (V, E)$ be a directed graph. A **strongly connected component** of G is a subset $U \subseteq V$ of maximal size in which for any pair of vertices $u, v \in U$ there exist both directed path from u to v and a directed path form v to u.

10.1.1 Depth First Search (DFS)

As its name implies, depth-first search searches "deeper" in the graph whenever possible. Depth-first search explores edges out of the most recently discovered vertex v that still has unexplored edges leaving it. Once all of v's edges have been explored, the search "backtracks" to explore edges leaving the vertex from which v was discovered. This process continues until all vertices that are reachable from the original source vertex have been discovered. If any undiscovered vertices remain, then depth-first search selects one of them as a new source, repeating the search from that source. The algorithm repeats this entire process until it has discovered every vertex.

```
1  DFS( G):
2  for v ∈ V do
3  |  v.visited ← False
4  end
5  time ← 1
6  for v ∈ V do
7  |  if not v.visited then
8  |  |  π (v) ← null
9  |  |  Explore( G, v )
10 |  end
11 end
```

```
1  Explore(G, v):
2  Previsit(v)
3  for (v, u) ∈ E do
4  |  if not u.visited then
5  |  |  π (u) ← v
6  |  |  Explore( G, u )
7  |  end
8  end
9  Postvisit(v)
```

```
1  Previsit(v):
2  pre(v) ← time
3  time ← time +1
```

```
1  Postvisit(v):
2  post(v) ← time
3  time ← time +1
```

Properties of depth-first search. Depth-first search yields valuable information about the structure of a graph. Perhaps the most basic property of depth-first search is that the predecessor subgraph G_π does indeed form a forest of trees since the structure of the depth-first trees exactly mirrors the structure of recursive calls of explore-function. That is, $u = \pi(v)$ if and only if explore(G, v) was called during a search of u's adjacency list.

Additionally, vertex v is a descendant of vertex u in the depth-first forest if and only if v is discovered during the time in which u is gray. Another important property of depth-first search is that discovery and finish times have a parenthesis structure. If the explore procedure were to print a left parenthesis "$(u$" when it discovers vertex u and to print a right parenthesis "$u)$" when it finishes u, then the printed expression would be well-formed in the sense that the parentheses are properly nested.

The following theorem provides another way to characterize the parenthesis structure.

Theorem 10.1.1 (Parenthesis theorem)**.** *In any depth-first search of a (directed or undirected) graph $G = (V, E)$, for any two vertices u and v, exactly one of the following three conditions holds:*

1. *the intervals [pre(u), post(u)] and [pre(v), post(v)] are entirely disjoint, and neither u nor v is a descendant of the other in the depth-first forest.*

2. *the interval [pre(u), post(u)] is contained entirely within the interval [pre(v), post(v)], and u is a descendant of v in a depth-first tree, or*

3. *the interval [pre(v), post(v)] is contained entirely within the interval [pre(u), post(u)], and v is a descendant of u in a depth-first tree.*

Proof. Assume without loss of generality that pre(u) < pre(v). Split to the following:

1. Either pre(v) < post(u). In that case, we will prove, by induction on pre(v) − pre(u), that for any u, v satisfies the relations, the third case holds.
   (a) Base. pre(v) − pre(u) = 1, Then clearly $\{u, v\}$, i.e v is a direct child of u. Showing that the value of post(v) has to be set before post(v) is left as an exercise.
   (b) Assumption. Assume correctness for any pre(v) − pre(u) < t < post(u).
   (c) Step. Consider $t > 1$ such pre(v) − pre(u) = t. Since $t > 1$ there is must to be vertex w for which pre(u) < pre(w) < pre(v) = t. Splits again:
      i. Either post(w) > pre(v). Observes that:

$$\text{pre}(v) - \text{pre}(w) < \text{pre}(v) - \text{pre}(u) = t$$

      and also:

$$\text{pre}(w) - \text{pre}(u) < \text{pre}(v) - \text{pre}(u) = t$$

      Therefore by the induction assumption:

$$[\text{pre}(v), \text{post}(v)] \subset [\text{pre}(w), \text{post}(w)] \subset [\text{pre}(u), \text{post}(u)]$$

      and in addition w is a descendant of u and v is a descendant of w. Hence v is a descendant of u and the third case holds.
      ii. Or post(w) < pre(v) for any w satisfies pre(u) < pre(w) < pre(v). That means that any call for **Explore**(G, w) at line 6 (over suited w's) returned, and at time t a new child of u has been discovered[1], namely v is a direct child of u and we back to the base.

2. Or, post(u) < pre(v), and by definition, pre(u) < post(u) < pre(v) < post(v) and thus the intervals [pre(u), post(u)] and [pre(v), post(v)] are disjoint.

   Showing that v is not a descendant of u can be proved in similar manner to the above, by induction on pre(v) − post(u). Completing the proof is left as an exercise.

□

Corollary 10.1.1. Vertex v is a proper descendant of vertex u in the depth-first forest for a (directed or undirected) graph G if and only if pre(u) < pre(v) < post(v) < post(u).

[1] otherwise we get a contradiction for post(u) > t

10.2 DFS on DAGS

the pre is well calibrated on DAGS.

Claim 10.2.1. *Let $G = (V, E)$ be a DAG, and let $v, u \in V$ such $u \to v$. Then for any $w \in V$ the call **DFS**(G, w) assigns post$(u) >$ post(v).*

Claim 10.2.2. *Define the relation $v \sim u$ to holds if u and v are on the same strong connected components. Then:*

1. *$\sim$ is an equivalence relation.*
2. *Define the graph $G' = (V', E')$ such that V' are the equivalence class respecting to $\sim$ and $\{u, v\} \in E'$ if there is a directed path in G from a vertex in u into a vertex in v. Then G' is a DAG.*

Claim 10.2.3. *Let u the vertex with the minimal post value, then **Explore**(G, u) colorize only the vertices on u's strong connected components.*