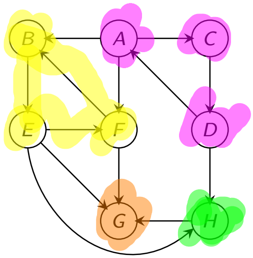
DFS in Directed Graphs, Strong Connected Components, and DAGs

Lecture 2

January 20, 2011

Strong Connected Components (SCCs)



Algorithmic Problem

Find all SCCs of a given directed graph.

Previous lecture: saw an $\mathbf{O(n \cdot (n + m))}$ time algorithm.

This lecture: $\mathbf{O(n + m)}$ time algorithm.

Graph of SCCs

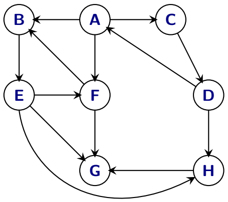


Figure: Graph **G**

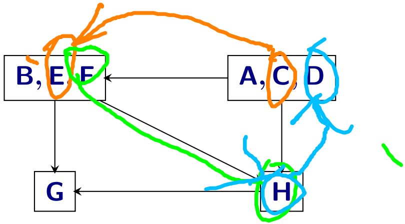


Figure: Graph of s **G**

Meta-graph of SCCs

Let $\mathbf{S_1, S_2, \ldots S_k}$ be the SCCs of **G**. The graph of SCCs is $\mathbf{G}^{\mathrm{SCC}}$

- Vertices are $\mathbf{S_1, S_2, \ldots S_k}$
- There is an edge $\mathbf{(S_i, S_j)}$ if there is some $\mathbf{u} \in \mathbf{S_i}$ and $\mathbf{v} \in \mathbf{S_j}$ such that $\mathbf{(u, v)}$ is an edge in **G**.

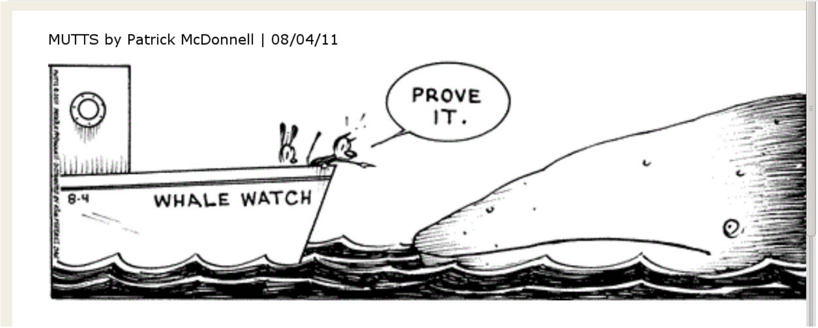
Reversal and SCCs

Proposition

For any graph $\mathbf{G}$, *the graph of* SCC*s of* $\mathbf{G}^{\mathbf{rev}}$ *is the same as the reversal of* $\mathbf{G}^{\mathbf{SCC}}$.

Proof.

Exercise. □



SCCs and DAGs

Proposition

For any graph $\mathbf{G}$, *the graph* $\mathbf{G}^{\mathrm{SCC}}$ *has no directed cycle.*

Proof.

If $\mathbf{G}^{\mathrm{SCC}}$ has a cycle $\mathbf{S}_1, \mathbf{S}_2, \ldots, \mathbf{S}_k$ then $\mathbf{S}_1 \cup \mathbf{S}_2 \cup \cdots \cup \mathbf{S}_k$ is an SCC in $\mathbf{G}$. Formal details: exercise. □

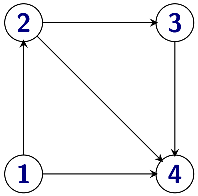
Part I

Directed Acyclic Graphs

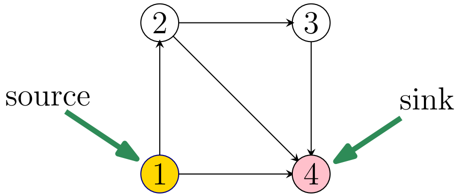
Directed Acyclic Graphs

Definition

A directed graph **G** is a **directed acyclic graph** (DAG) if there is no directed cycle in **G**.



Sources and Sinks



Definition

- A vertex **u** is a **source** if it has no in-coming edges.
- A vertex **u** is a **sink** if it has no out-going edges.

Simple DAG Properties

- Every DAG **G** has at least one source and at least one sink.
- If **G** is a DAG if and only if $\mathbf{G}^{\mathsf{rev}}$ is a DAG.
- **G** is a DAG if and only each node is in its own strong connected component.

Formal proofs: exercise.

Simple DAG Properties

- Every DAG **G** has at least one source and at least one sink.
- If **G** is a DAG if and only if $\mathbf{G}^{\mathrm{rev}}$ is a DAG.
- **G** is a DAG if and only each node is in its own strong connected component.

Formal proofs: exercise.

Simple DAG Properties

- Every DAG **G** has at least one source and at least one sink.
- If **G** is a DAG if and only if $\mathbf{G}^{\mathbf{rev}}$ is a DAG.
- **G** is a DAG if and only each node is in its own strong connected component.

Formal proofs: exercise.

Simple DAG Properties

- Every DAG **G** has at least one source and at least one sink.
- If **G** is a DAG if and only if $\mathbf{G}^{\mathbf{rev}}$ is a DAG.
- **G** is a DAG if and only each node is in its own strong connected component.

Formal proofs: exercise.

Simple DAG Properties

- Every DAG $\mathbf{G}$ has at least one source and at least one sink.
- If $\mathbf{G}$ is a DAG if and only if $\mathbf{G}^{\text{rev}}$ is a DAG.
- $\mathbf{G}$ is a DAG if and only each node is in its own strong connected component.

Formal proofs: exercise.

Topological Ordering/Sorting

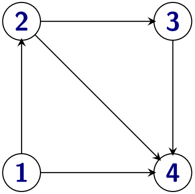


Figure: Graph $\mathbf{G}$

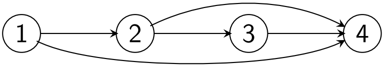


Figure: Topological Ordering of $\mathbf{G}$

Definition

A **topological ordering/topological sorting** of $\mathbf{G} = (\mathbf{V}, \mathbf{E})$ is an ordering $<$ on $\mathbf{V}$ such that if $(\mathbf{u}, \mathbf{v}) \in \mathbf{E}$ then $\mathbf{u} < \mathbf{v}$.

DAGs and Topological Sort

Lemma

A directed graph $\mathbf{G}$ can be topologically ordered iff it is a DAG.

Proof.

$\Longrightarrow$: Suppose $\mathbf{G}$ is not a DAG and has a topological ordering $\prec$. $\mathbf{G}$ has a cycle $\mathbf{C} = \mathbf{u}_1, \mathbf{u}_2, \ldots, \mathbf{u}_k, \mathbf{u}_1$.

Then $\mathbf{u}_1 \prec \mathbf{u}_2 \prec \ldots \prec \mathbf{u}_k \prec \mathbf{u}_1$!

That is... $\mathbf{u}_1 \prec \mathbf{u}_1$.

A contradiction (to $\prec$ being an order).

Not possible to topologically order the vertices. □

DAGs and Topological Sort

Lemma

A directed graph $\mathbf{G}$ can be topologically ordered iff it is a DAG.

Continued.

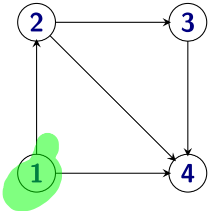
$\Leftarrow$: Consider the following algorithm:

- Pick a source $\mathbf{u}$, output it.
- Remove $\mathbf{u}$ and all edges out of $\mathbf{u}$.
- Repeat until graph is empty.
- Exercise: prove this gives an ordering.

$\square$

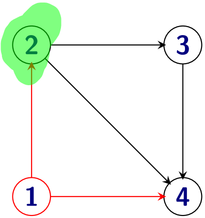
Exercise: show above algorithm can be implemented in $\mathbf{O(m + n)}$ time.

Topological Sort: An Example



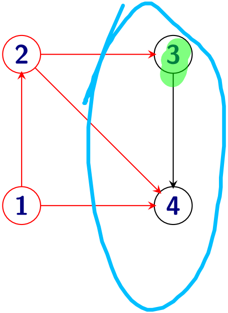
Output: 1 2 3 4

Topological Sort: An Example



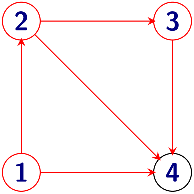
Output: 1 2 3 4

Topological Sort: An Example



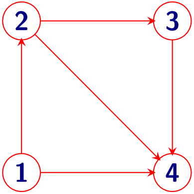
Output: 1 2 3 4

Topological Sort: An Example



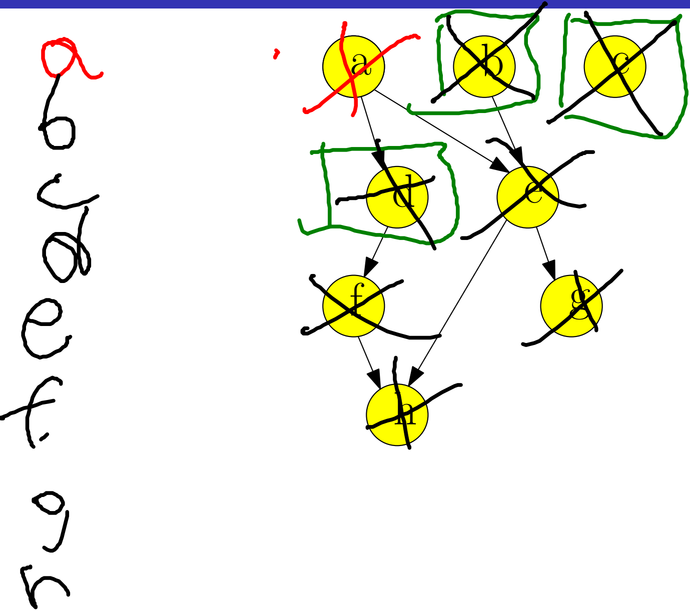
Output: 1 2 3 4

Topological Sort: An Example

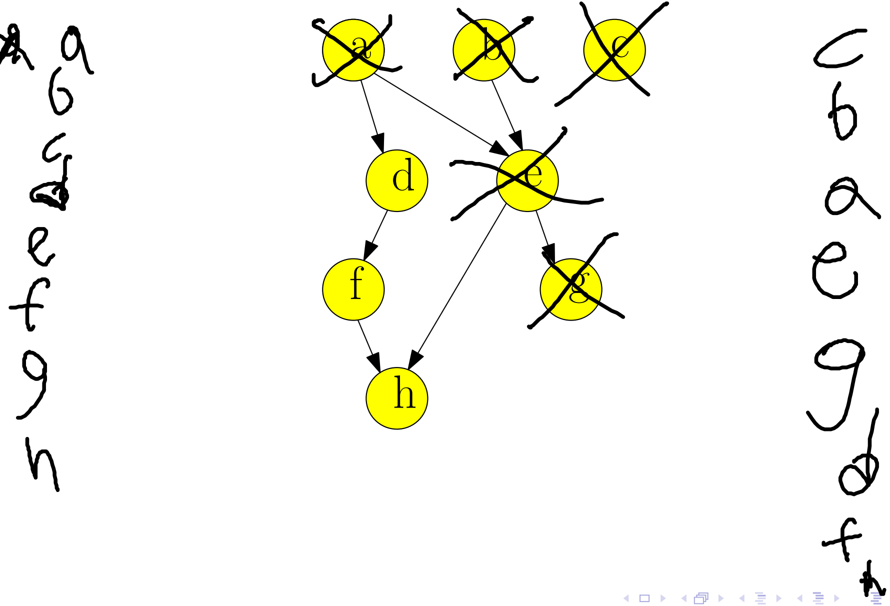


Output: 1 2 3 4

Topological Sort: Another Example



Topological Sort: Another Example



DAGs and Topological Sort

Note: A DAG **G** may have many different topological sorts.

Question: What is a DAG with the most number of distinct topological sorts for a given number **n** of vertices?

n singletons

Question: What is a DAG with the least number of distinct topological sorts for a given number **n** of vertices?

A Linked list

Using DFS...

... to check for Acylicity and compute Topological Ordering

Question

Given **G**, is it a DAG? If it is, generate a topological sort.

DFS based algorithm:

- Compute **DFS(G)**
- If there is a back edge then **G** is not a DAG.
- Otherwise output nodes in decreasing post-visit order.

Correctness relies on the following:

Proposition

$\mathbf{G}$ is a DAG iff there is no back-edge in **DFS(G)**.

Proposition

If $\mathbf{G}$ is a DAG and $\mathrm{post}(\mathbf{v}) > \mathrm{post}(\mathbf{u})$, then $(\mathbf{u}, \mathbf{v})$ is not in $\mathbf{G}$.

Using DFS...

... to check for Acylicity and compute Topological Ordering

Question

Given $\mathbf{G}$, is it a DAG? If it is, generate a topological sort.

DFS based algorithm:

- Compute **DFS(G)**
- If there is a back edge then $\mathbf{G}$ is not a DAG.
- Otherwise output nodes in decreasing post-visit order.

Correctness relies on the following:

Proposition

$\mathbf{G}$ is a DAG iff there is no back-edge in **DFS(G)**.

Proposition

If $\mathbf{G}$ is a DAG and $\mathrm{post}(\mathbf{v}) > \mathrm{post}(\mathbf{u})$, then $(\mathbf{u}, \mathbf{v})$ is not in $\mathbf{G}$.

Using DFS...

... to check for Acylicity and compute Topological Ordering

Question

Given $\mathbf{G}$, is it a DAG? If it is, generate a topological sort.

DFS based algorithm:

- Compute **DFS(G)**
- If there is a back edge then $\mathbf{G}$ is not a DAG.
- Otherwise output nodes in decreasing post-visit order.

Correctness relies on the following:

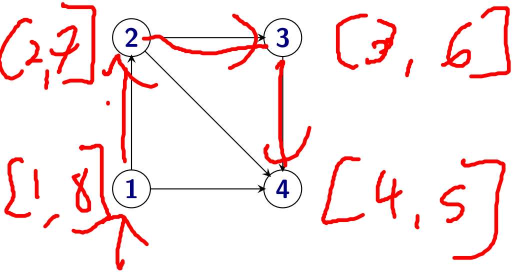
Proposition

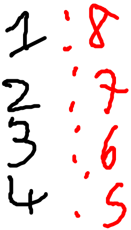
$\mathbf{G}$ *is a* DAG *iff there is no back-edge in* **DFS(G)**.

Proposition

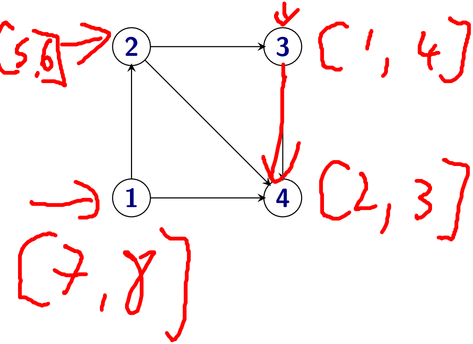
If $\mathbf{G}$ *is a* DAG *and* $\mathrm{post}(\mathbf{v}) > \mathrm{post}(\mathbf{u})$, *then* $(\mathbf{u}, \mathbf{v})$ *is not in* $\mathbf{G}$.

Example





Example



Back edge and Cycles

Proposition

$\mathbf{G}$ *has a cycle iff there is a back-edge in* $\mathbf{DFS(G)}$.

Proof.

If: $(\mathbf{u}, \mathbf{v})$ is a back edge implies there is a cycle $\mathbf{C}$ consisting of the path from $\mathbf{v}$ to $\mathbf{u}$ in **DFS** search tree and the edge $(\mathbf{u}, \mathbf{v})$.

Only if: Suppose there is a cycle $\mathbf{C} = \mathbf{v}_1 \rightarrow \mathbf{v}_2 \rightarrow \ldots \rightarrow \mathbf{v}_k \rightarrow \mathbf{v}_1$.
Let $\mathbf{v}_i$ be first node in $\mathbf{C}$ visited in **DFS**.
All other nodes in $\mathbf{C}$ are descendents of $\mathbf{v}_i$ since they are reachable from $\mathbf{v}_i$.
Therefore, $(\mathbf{v}_{i-1}, \mathbf{v}_i)$ (or $(\mathbf{v}_k, \mathbf{v}_1)$ if $\mathbf{i} = 1$) is a back edge. □

Back edge and Cycles

Proposition

*$\mathbf{G}$ has a cycle iff there is a back-edge in **DFS**$(\mathbf{G})$.*

Proof.

If: $(\mathbf{u}, \mathbf{v})$ is a back edge implies there is a cycle $\mathbf{C}$ consisting of the path from $\mathbf{v}$ to $\mathbf{u}$ in **DFS** search tree and the edge $(\mathbf{u}, \mathbf{v})$.

Only if: Suppose there is a cycle $\mathbf{C} = \mathbf{v}_1 \rightarrow \mathbf{v}_2 \rightarrow \ldots \rightarrow \mathbf{v}_k \rightarrow \mathbf{v}_1$.
Let $\mathbf{v}_i$ be first node in $\mathbf{C}$ visited in **DFS**.
All other nodes in $\mathbf{C}$ are descendents of $\mathbf{v}_i$ since they are reachable from $\mathbf{v}_i$.
Therefore, $(\mathbf{v}_{i-1}, \mathbf{v}_i)$ (or $(\mathbf{v}_k, \mathbf{v}_1)$ if $\mathbf{i} = 1$) is a back edge. □

DAGs and Partial Orders

Definition

A **partially ordered set** is a set $\mathbf{S}$ along with a binary relation $\preceq$ such that $\preceq$ is

1. **reflexive** ($\mathbf{a} \preceq \mathbf{a}$ for all $\mathbf{a} \in \mathbf{V}$),
2. **anti-symmetric** ($\mathbf{a} \preceq \mathbf{b}$ and $\mathbf{a} \neq \mathbf{b}$ implies $\mathbf{b} \not\preceq \mathbf{a}$), and
3. **transitive** ($\mathbf{a} \preceq \mathbf{b}$ and $\mathbf{b} \preceq \mathbf{c}$ implies $\mathbf{a} \preceq \mathbf{c}$).

Example: For numbers in the plane define $(\mathbf{x}, \mathbf{y}) \preceq (\mathbf{x}', \mathbf{y}')$ iff $\mathbf{x} \leq \mathbf{x}'$ and $\mathbf{y} \leq \mathbf{y}'$.

Observation: A *finite* partially ordered set is equivalent to a DAG. (No equal elements.)

Observation: A topological sort of a DAG corresponds to a complete (or total) ordering of the underlying partial order.

DAGs and Partial Orders

Definition

A **partially ordered set** is a set $\mathbf{S}$ along with a binary relation $\preceq$ such that $\preceq$ is

1. **reflexive** ($\mathbf{a} \preceq \mathbf{a}$ for all $\mathbf{a} \in \mathbf{V}$),
2. **anti-symmetric** ($\mathbf{a} \preceq \mathbf{b}$ and $\mathbf{a} \neq \mathbf{b}$ implies $\mathbf{b} \not\preceq \mathbf{a}$), and
3. **transitive** ($\mathbf{a} \preceq \mathbf{b}$ and $\mathbf{b} \preceq \mathbf{c}$ implies $\mathbf{a} \preceq \mathbf{c}$).

Example: For numbers in the plane define $(\mathbf{x}, \mathbf{y}) \preceq (\mathbf{x}', \mathbf{y}')$ iff $\mathbf{x} \leq \mathbf{x}'$ and $\mathbf{y} \leq \mathbf{y}'$.

Observation: A *finite* partially ordered set is equivalent to a DAG. (No equal elements.)

Observation: A topological sort of a DAG corresponds to a complete (or total) ordering of the underlying partial order.

DAGs and Partial Orders

Definition

A **partially ordered set** is a set $\mathbf{S}$ along with a binary relation $\preceq$ such that $\preceq$ is

1. **reflexive** ($\mathbf{a} \preceq \mathbf{a}$ for all $\mathbf{a} \in \mathbf{V}$),
2. **anti-symmetric** ($\mathbf{a} \preceq \mathbf{b}$ and $\mathbf{a} \neq \mathbf{b}$ implies $\mathbf{b} \not\preceq \mathbf{a}$), and
3. **transitive** ($\mathbf{a} \preceq \mathbf{b}$ and $\mathbf{b} \preceq \mathbf{c}$ implies $\mathbf{a} \preceq \mathbf{c}$).

Example: For numbers in the plane define $(\mathbf{x}, \mathbf{y}) \preceq (\mathbf{x}', \mathbf{y}')$ iff $\mathbf{x} \leq \mathbf{x}'$ and $\mathbf{y} \leq \mathbf{y}'$.

Observation: A *finite* partially ordered set is equivalent to a DAG. (No equal elements.)

Observation: A topological sort of a DAG corresponds to a complete (or total) ordering of the underlying partial order.

Part II

Linear time algorithm for finding all strong connected components of a directed graph

Finding all SCCs of a Directed Graph

Problem

Given a directed graph $G = (V, E)$, output *all* its strong connected components.

Straightforward algorithm:

```
For each vertex u ∈ V do
    find SCC(G, u) the strong component containing u as follows:
        Obtain rch(G, u) using DFS(G, u)
        Obtain rch(G^rev, u) using DFS(G^rev, u)
        Output SCC(G, u) = rch(G, u) ∩ rch(G^rev, u)
```

Running time: $O(n(n + m))$

Is there an $O(n + m)$ time algorithm?

Finding all SCCs of a Directed Graph

Problem

Given a directed graph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, output *all* its strong connected components.

Straightforward algorithm:

```
For each vertex u ∈ V do
    find SCC(G, u) the strong component containing u as follows:
        Obtain rch(G, u) using DFS(G, u)
        Obtain rch(G^rev, u) using DFS(G^rev, u)
        Output SCC(G, u) = rch(G, u) ∩ rch(G^rev, u)
```

Running time: $\mathbf{O}(\mathbf{n}(\mathbf{n} + \mathbf{m}))$

Is there an $\mathbf{O}(\mathbf{n} + \mathbf{m})$ time algorithm?

Finding all SCCs of a Directed Graph

Problem

Given a directed graph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, output *all* its strong connected components.

Straightforward algorithm:

```
For each vertex u ∈ V do
    find SCC(G, u) the strong component containing u as follows:
        Obtain rch(G, u) using DFS(G, u)
        Obtain rch(G^rev, u) using DFS(G^rev, u)
        Output SCC(G, u) = rch(G, u) ∩ rch(G^rev, u)
```

Running time: $\mathbf{O(n(n + m))}$

Is there an $\mathbf{O(n + m)}$ time algorithm?

Structure of a Directed Graph

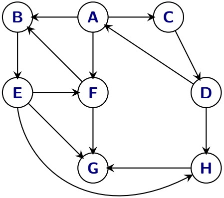


Figure: Graph **G**

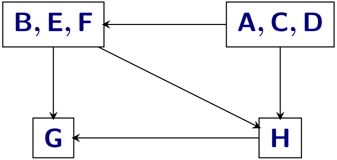


Figure: Graph of SCCs $\mathbf{G}^{\mathrm{SCC}}$

Proposition

For a directed graph **G**, *its meta-graph* $\mathbf{G}^{\mathrm{SCC}}$ *is a* DAG.

Linear-time Algorithm for SCCs: Ideas

Exploit structure of meta-graph.

Algorithm

- Let $\mathbf{u}$ be a vertex in a sink SCC of $\mathbf{G}^{\mathrm{SCC}}$
- Do **DFS**$(\mathbf{u})$ to compute $\mathrm{SCC}(\mathbf{u})$
- Remove $\mathrm{SCC}(\mathbf{u})$ and repeat

Justification

- **DFS**$(\mathbf{u})$ only visits vertices (and edges) in $\mathrm{SCC}(\mathbf{u})$
- **DFS**$(\mathbf{u})$ takes time proportional to size of $\mathrm{SCC}(\mathbf{u})$
- Therefore, total time $\mathbf{O}(\mathbf{n}+\mathbf{m})$!

Big Challenge(s)

How do we find a vertex in the sink SCC of $\mathbf{G}^{\mathrm{SCC}}$?

Can we obtain an *implicit* topological sort of $\mathbf{G}^{\mathrm{SCC}}$ without computing $\mathbf{G}^{\mathrm{SCC}}$?

Answer: $\mathbf{DFS}(\mathbf{G})$ gives some information!

Big Challenge(s)

How do we find a vertex in the sink SCC of $\mathbf{G}^{\mathrm{SCC}}$?

Can we obtain an *implicit* topological sort of $\mathbf{G}^{\mathrm{SCC}}$ without computing $\mathbf{G}^{\mathrm{SCC}}$?

Answer: $\mathbf{DFS}(\mathbf{G})$ gives some information!

Big Challenge(s)

How do we find a vertex in the sink SCC of $\mathbf{G}^{\mathrm{SCC}}$?

Can we obtain an *implicit* topological sort of $\mathbf{G}^{\mathrm{SCC}}$ without computing $\mathbf{G}^{\mathrm{SCC}}$?

Answer: **DFS(G)** gives some information!

Post-visit times of SCCs

Definition

Given $\mathbf{G}$ and a SCC $\mathbf{S}$ of $\mathbf{G}$, define $\mathrm{post}(\mathbf{S}) = \max_{u \in S} \mathrm{post}(\mathbf{u})$ where post numbers are with respect to some $\mathbf{DFS}(\mathbf{G})$.

An Example

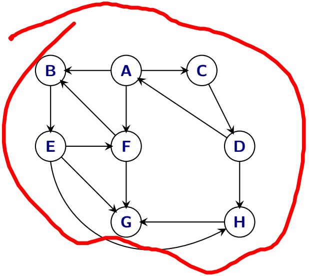


Figure: Graph **G**

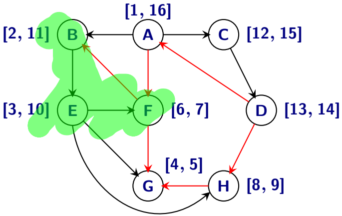


Figure: Graph with pre-post times for **DFS**(**A**); black edges in tree

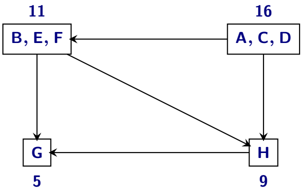


Figure: $\mathbf{G}^{\mathrm{SCC}}$ with post times

G^{SCC} and post-visit times

Proposition

If S *and* S' *are* SCCs *in* G *and* (S, S') *is an edge in* G^{SCC} *then* $post(S) > post(S')$.

Proof.

Let u be first vertex in $S \cup S'$ that is visited.

- If $u \in S$ then all of S' will be explored before $DFS(u)$ completes.
- If $u \in S'$ then all of S' will be explored before any of S.

□

A False Statement: If S and S' are SCCs in G and (S, S') is an edge in G^{SCC} then for *every* $u \in S$ and $u' \in S'$, $post(u) > post(u')$.

G^{SCC} and post-visit times

Proposition

If $\mathbf{S}$ *and* $\mathbf{S'}$ *are* SCC*s in* $\mathbf{G}$ *and* $(\mathbf{S}, \mathbf{S'})$ *is an edge in* $\mathbf{G}^{\mathrm{SCC}}$ *then* $\mathrm{post}(\mathbf{S}) > \mathrm{post}(\mathbf{S'})$.

Proof.

Let $\mathbf{u}$ be first vertex in $\mathbf{S} \cup \mathbf{S'}$ that is visited.

- If $\mathbf{u} \in \mathbf{S}$ then all of $\mathbf{S'}$ will be explored before $\mathbf{DFS}(\mathbf{u})$ completes.
- If $\mathbf{u} \in \mathbf{S'}$ then all of $\mathbf{S'}$ will be explored before any of $\mathbf{S}$.

□

A False Statement: If $\mathbf{S}$ and $\mathbf{S'}$ are SCCs in $\mathbf{G}$ and $(\mathbf{S}, \mathbf{S'})$ is an edge in $\mathbf{G}^{\mathrm{SCC}}$ then for *every* $\mathbf{u} \in \mathbf{S}$ and $\mathbf{u'} \in \mathbf{S'}$, $\mathrm{post}(\mathbf{u}) > \mathrm{post}(\mathbf{u'})$.

Topological ordering of $\mathbf{G}^{\mathrm{SCC}}$

Corollary

Ordering SCC*s in decreasing order of* $\mathrm{post}(\mathbf{S})$ *gives a topological ordering of* $\mathbf{G}^{\mathrm{SCC}}$

Recall: for a DAG, ordering nodes in decreasing post-visit order gives a topological sort.

So...

DFS(G) gives some information on topological ordering of $\mathbf{G}^{\mathrm{SCC}}$!

Topological ordering of $\mathbf{G}^{\mathrm{SCC}}$

Corollary

Ordering SCC*s in decreasing order of* $\mathrm{post}(\mathbf{S})$ *gives a topological ordering of* $\mathbf{G}^{\mathrm{SCC}}$

Recall: for a DAG, ordering nodes in decreasing post-visit order gives a topological sort.

So...
DFS(G) gives some information on topological ordering of $\mathbf{G}^{\mathrm{SCC}}$!

Finding Sources

Proposition

The vertex $\mathbf{u}$ *with the highest post visit time belongs to a source* SCC *in* $\mathbf{G}^{\mathrm{SCC}}$

Proof.

- $\mathbf{post}(\mathbf{SCC}(\mathbf{u})) = \mathbf{post}(\mathbf{u})$
- Thus, $\mathbf{post}(\mathbf{SCC}(\mathbf{u}))$ is highest and will be output first in topological ordering of $\mathbf{G}^{\mathrm{SCC}}$.

□

Finding Sources

Proposition

The vertex $\mathbf{u}$ *with the highest post visit time belongs to a source* SCC *in* $\mathbf{G}^{\mathrm{SCC}}$

Proof.

- $\mathbf{post(SCC(u)) = post(u)}$
- Thus, $\mathbf{post(SCC(u))}$ is highest and will be output first in topological ordering of $\mathbf{G}^{\mathrm{SCC}}$.

□

Finding Sinks

Proposition

The vertex $\mathbf{u}$ *with highest post visit time in* $\mathbf{DFS}(\mathbf{G}^{\mathrm{rev}})$ *belongs to a sink SCC of* $\mathbf{G}$.

Proof.

- $\mathbf{u}$ belongs to source SCC of $\mathbf{G}^{\mathrm{rev}}$
- Since graph of SCCs of $\mathbf{G}^{\mathrm{rev}}$ is the reverse of $\mathbf{G}^{\mathrm{SCC}}$, $\mathrm{SCC}(\mathbf{u})$ is sink SCC of $\mathbf{G}$. □

Finding Sinks

Proposition

The vertex $\mathbf{u}$ *with highest post visit time in* **DFS**$(\mathbf{G}^{\mathbf{rev}})$ *belongs to a sink SCC of* $\mathbf{G}$.

Proof.

- $\mathbf{u}$ belongs to source SCC of $\mathbf{G}^{\mathbf{rev}}$
- Since graph of SCCs of $\mathbf{G}^{\mathbf{rev}}$ is the reverse of $\mathbf{G}^{\mathbf{SCC}}$, $\mathrm{SCC}(\mathbf{u})$ is sink SCC of $\mathbf{G}$. □

Linear Time Algorithm

...for computing the strong connected components in $\mathbf{G}$

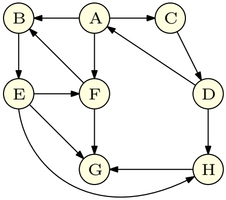
```
Do DFS(G^rev) and sort vertices in decreasing post order.
Mark all nodes as unvisited
for each u in the computed order do
    if u is not visited then
        DFS(u)
        Let S_u be the nodes reached by u
        Output S_u as a strong connected component
        Remove S_u from G
```

Analysis

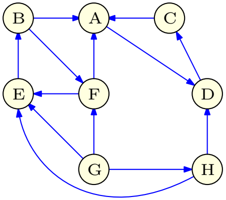
Running time is $O(n + m)$. (Exercise)

Linear Time Algorithm: An Example - Initial steps

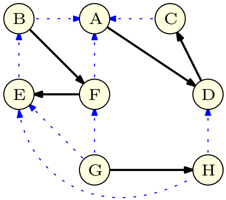
Graph **G**:



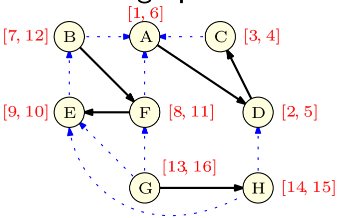
Reverse graph $\mathbf{G}^{\mathbf{rev}}$:



DFS of reverse graph:



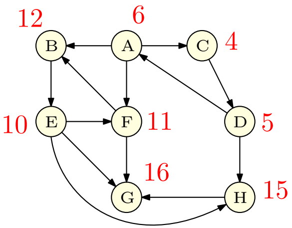
Pre/Post **DFS** numbering of reverse graph:



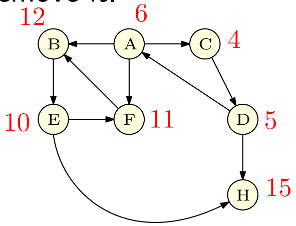
Linear Time Algorithm: An Example

Removing connected components: 1

Original graph **G** with rev post numbers:



Do **DFS** from vertex **G** remove it.

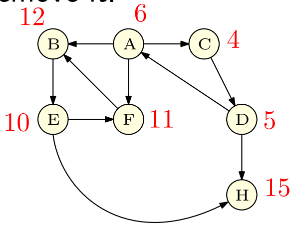


SCC computed:
{G}

Linear Time Algorithm: An Example

Removing connected components: 2

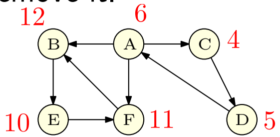
Do **DFS** from vertex **G** remove it.



SCC computed:
{G}

$\Longrightarrow$

Do **DFS** from vertex **H**, remove it.

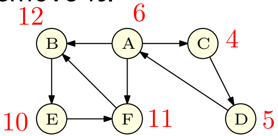


SCC computed:
{G}, {H}

Linear Time Algorithm: An Example

Removing connected components: 3

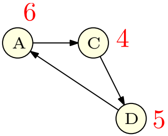
Do **DFS** from vertex **H**, remove it.



SCC computed:
{G}, {H}

$\Longrightarrow$

Do **DFS** from vertex **F**
Remove visited vertices:
{F, B, E}.

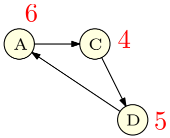


SCC computed:
{G}, {H}, {F, B, E}

Linear Time Algorithm: An Example

Removing connected components: 4

Do **DFS** from vertex **F**
Remove visited vertices:
{F, B, E}.



SCC computed:
{G}, {H}, {F, B, E}

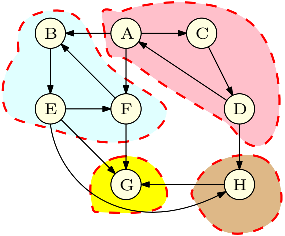
$\Longrightarrow$

Do **DFS** from vertex **A**
Remove visited vertices:
{A, C, D}.

SCC computed:
{G}, {H}, {F, B, E}, {A, C, D}

Linear Time Algorithm: An Example

Final result



SCC computed:

{G}, {H}, {F, B, E}, {A, C, D}

Which is the correct answer!

Obtaining the meta-graph from strong connected components

Exercise: Given all the strong connected components of a directed graph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$ show that the meta-graph $\mathbf{G}^{\mathrm{SCC}}$ can be obtained in $\mathbf{O}(\mathbf{m} + \mathbf{n})$ time.

Correctness: more details

- let $S_1, S_2, \ldots, S_k$ be strong components in G
- Strong components of G^{rev} and G are same and meta-graph of G is reverse of meta-graph of G^{rev}.
- consider $DFS(G^{rev})$ and let $u_1, u_2, \ldots, u_k$ be such that $\mathrm{post}(u_i) = \mathrm{post}(S_i) = \max_{v \in S_i} \mathrm{post}(v)$.
- Assume without loss of generality that $\mathbf{post}(u_k) > \mathbf{post}(u_{k-1}) \geq \ldots \geq \mathbf{post}(u_1)$ (renumber otherwise). Then $S_k, S_{k-1}, \ldots, S_1$ is a topological sort of meta-graph of G^{rev} and hence $S_1, S_2, \ldots, S_k$ is a topological sort of the meta-graph of G.
- u_k has highest post number and $DFS(u_k)$ will explore all of S_k which is a sink component in G.
- After S_k is removed u_{k-1} has highest post number and $DFS(u_{k-1})$ will explore all of S_{k-1} which is a sink component in remaining graph $G - S_k$. Formal proof by induction.

Correctness: more details

- let $S_1, S_2, \ldots, S_k$ be strong components in G
- Strong components of G^{rev} and G are same and meta-graph of G is reverse of meta-graph of G^{rev}.
- consider $\text{DFS}(G^{rev})$ and let $u_1, u_2, \ldots, u_k$ be such that $\text{post}(u_i) = \text{post}(S_i) = \max_{v \in S_i} \text{post}(v)$.
- Assume without loss of generality that $\text{post}(u_k) > \text{post}(u_{k-1}) \geq \ldots \geq \text{post}(u_1)$ (renumber otherwise). Then $S_k, S_{k-1}, \ldots, S_1$ is a topological sort of meta-graph of G^{rev} and hence $S_1, S_2, \ldots, S_k$ is a topological sort of the meta-graph of G.
- u_k has highest post number and $\text{DFS}(u_k)$ will explore all of S_k which is a sink component in G.
- After S_k is removed u_{k-1} has highest post number and $\text{DFS}(u_{k-1})$ will explore all of S_{k-1} which is a sink component in remaining graph $G - S_k$. Formal proof by induction.

Correctness: more details

- let $S_1, S_2, \ldots, S_k$ be strong components in G
- Strong components of G^{rev} and G are same and meta-graph of G is reverse of meta-graph of G^{rev}.
- consider **DFS**(G^{rev}) and let $u_1, u_2, \ldots, u_k$ be such that $\mathrm{post}(u_i) = \mathrm{post}(S_i) = \max_{v \in S_i} \mathrm{post}(v)$.
- Assume without loss of generality that $\mathrm{post}(u_k) > \mathrm{post}(u_{k-1}) \geq \ldots \geq \mathrm{post}(u_1)$ (renumber otherwise). Then $S_k, S_{k-1}, \ldots, S_1$ is a topological sort of meta-graph of G^{rev} and hence $S_1, S_2, \ldots, S_k$ is a topological sort of the meta-graph of G.
- u_k has highest post number and **DFS**(u_k) will explore all of S_k which is a sink component in G.
- After S_k is removed u_{k-1} has highest post number and **DFS**(u_{k-1}) will explore all of S_{k-1} which is a sink component in remaining graph $G - S_k$. Formal proof by induction.

Correctness: more details

- let $S_1, S_2, \ldots, S_k$ be strong components in G
- Strong components of G^{rev} and G are same and meta-graph of G is reverse of meta-graph of G^{rev}.
- consider **DFS**(G^{rev}) and let $u_1, u_2, \ldots, u_k$ be such that $\mathrm{post}(u_i) = \mathrm{post}(S_i) = \max_{v \in S_i} \mathrm{post}(v)$.
- Assume without loss of generality that $\mathbf{post}(u_k) > \mathbf{post}(u_{k-1}) \geq \ldots \geq \mathbf{post}(u_1)$ (renumber otherwise). Then $S_k, S_{k-1}, \ldots, S_1$ is a topological sort of meta-graph of G^{rev} and hence $S_1, S_2, \ldots, S_k$ is a topological sort of the meta-graph of G.
- u_k has highest post number and **DFS**(u_k) will explore all of S_k which is a sink component in G.
- After S_k is removed u_{k-1} has highest post number and **DFS**(u_{k-1}) will explore all of S_{k-1} which is a sink component in remaining graph $G - S_k$. Formal proof by induction.

Correctness: more details

- let $S_1, S_2, \ldots, S_k$ be strong components in G
- Strong components of G^{rev} and G are same and meta-graph of G is reverse of meta-graph of G^{rev}.
- consider DFS(G^{rev}) and let $u_1, u_2, \ldots, u_k$ be such that $\mathrm{post}(u_i) = \mathrm{post}(S_i) = \max_{v \in S_i} \mathrm{post}(v)$.
- Assume without loss of generality that $\mathrm{post}(u_k) > \mathrm{post}(u_{k-1}) \geq \ldots \geq \mathrm{post}(u_1)$ (renumber otherwise). Then $S_k, S_{k-1}, \ldots, S_1$ is a topological sort of meta-graph of G^{rev} and hence $S_1, S_2, \ldots, S_k$ is a topological sort of the meta-graph of G.
- u_k has highest post number and DFS(u_k) will explore all of S_k which is a sink component in G.
- After S_k is removed u_{k-1} has highest post number and DFS(u_{k-1}) will explore all of S_{k-1} which is a sink component in remaining graph $G - S_k$. Formal proof by induction.

Correctness: more details

- let $S_1, S_2, \ldots, S_k$ be strong components in G
- Strong components of G^{rev} and G are same and meta-graph of G is reverse of meta-graph of G^{rev}.
- consider $\mathsf{DFS}(G^{rev})$ and let $u_1, u_2, \ldots, u_k$ be such that $\mathrm{post}(u_i) = \mathrm{post}(S_i) = \max_{v \in S_i} \mathrm{post}(v)$.
- Assume without loss of generality that $\mathbf{post}(u_k) > \mathbf{post}(u_{k-1}) \geq \ldots \geq \mathbf{post}(u_1)$ (renumber otherwise). Then $S_k, S_{k-1}, \ldots, S_1$ is a topological sort of meta-graph of G^{rev} and hence $S_1, S_2, \ldots, S_k$ is a topological sort of the meta-graph of G.
- u_k has highest post number and $\mathsf{DFS}(u_k)$ will explore all of S_k which is a sink component in G.
- After S_k is removed u_{k-1} has highest post number and $\mathsf{DFS}(u_{k-1})$ will explore all of S_{k-1} which is a sink component in remaining graph $G - S_k$. Formal proof by induction.

Part III

An Application to `make`

make Utility [Feldman]

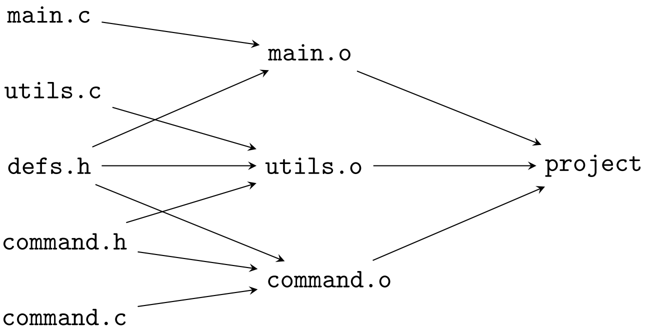
- Unix utility for automatically building large software applications
- A makefile specifies
  - Object files to be created,
  - Source/object files to be used in creation, and
  - How to create them

An Example `makefile`

```
project:  main.o utils.o command.o
    cc -o project main.o utils.o command.o

main.o:  main.c defs.h
    cc -c main.c
utils.o:  utils.c defs.h command.h
    cc -c utils.c
command.o:  command.c defs.h command.h
    cc -c command.c
```

makefile as a Digraph



Computational Problems for `make`

- Is the `makefile` reasonable?
- If it is reasonable, in what order should the object files be created?
- If it is not reasonable, provide helpful debugging information.
- If some file is modified, find the fewest compilations needed to make application consistent.

Algorithms for `make`

- Is the `makefile` reasonable? Is **G** a DAG?
- If it is reasonable, in what order should the object files be created? Find a topological sort of a DAG.
- If it is not reasonable, provide helpful debugging information. Output a cycle. More generally, output all strong connected components.
- If some file is modified, find the fewest compilations needed to make application consistent.
  - Find all vertices reachable (using **DFS**/**BFS**) from modified files in directed graph, and recompile them in proper order. Verify that one can find the files to recompile and the ordering in linear time.

Take away Points

- Given a directed graph **G**, its SCCs and the associated acyclic meta-graph $\mathbf{G}^{\mathrm{SCC}}$ give a structural decomposition of **G** that should be kept in mind.
- There is a **DFS** based linear time algorithm to compute all the SCCs and the meta-graph. Properties of **DFS** crucial for the algorithm.
- DAGs arise in many application and topological sort is a key property in algorithm design. Linear time algorithms to compute a topological sort (there can be many possible orderings so not unique).

Notes

Notes

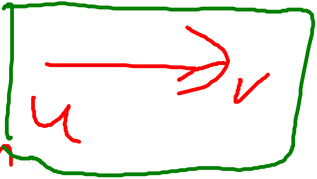
Notes

Notes

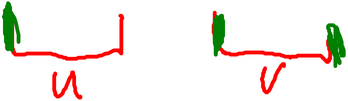
Assume $(u,v) \in E(G)$ ← contradiction

if $post(v) > post(u)$

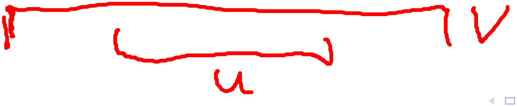
$pre(v) > pre(u)$ then



not possible



if $pre(v) < pre(u)$ then impossible



⇒ there is a cycle