Algorithms and Data Structures

DiGraphs – Directed Graphs

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Outline

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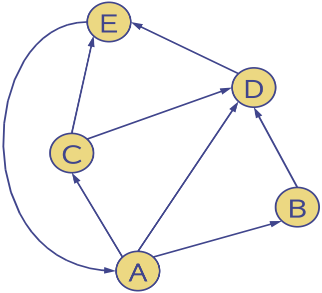
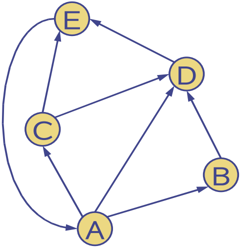
Digraphs

- A **digraph** is a graph whose edges are all directed
  - Short for “directed graph”
- Applications
  - one-way streets
  - flights
  - task scheduling



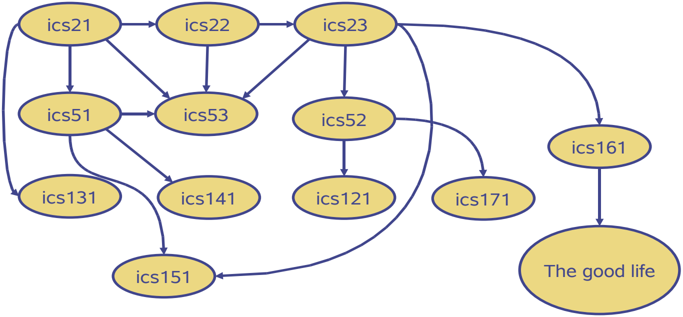
Digraph Properties



- A graph G=(V,E) such that
  - Each edge goes in one direction:
    - Edge (a,b) goes from a to b, but not b to a.
- If G is simple, $m \leq n(n-1)$.
- If we keep in-edges and out-edges in separate adjacency lists, we can perform listing of of the sets of in-edges and out-edges in time proportional to their size.

Digraph Application

- Scheduling: edge (a,b) means task a must be completed before b can be started



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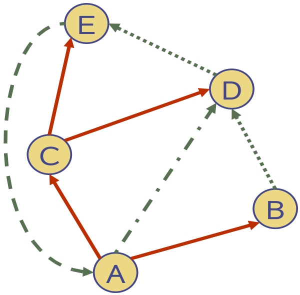
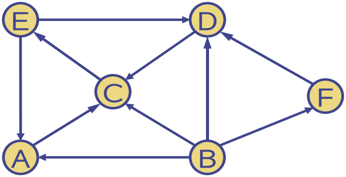
Directed DFS

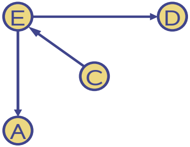
- We can specialize the traversal algorithms (DFS and BFS) to digraphs by traversing edges only along their direction
- In the directed DFS algorithm, we have four types of edges
  - discovery edges
  - back edges
  - forward edges
  - cross edges
- A directed DFS starting at a vertex s determines the vertices reachable from s

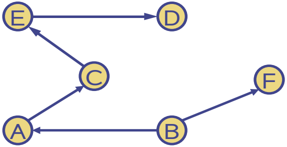


Reachability

- DFS tree rooted at v: vertices reachable from v via directed paths







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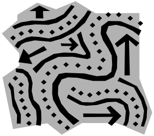
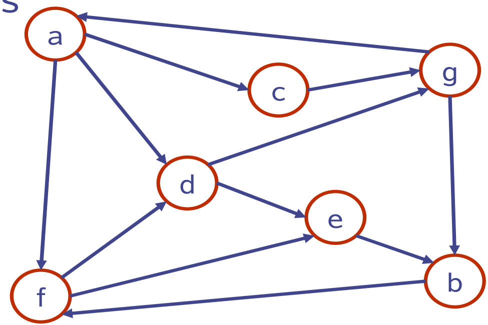


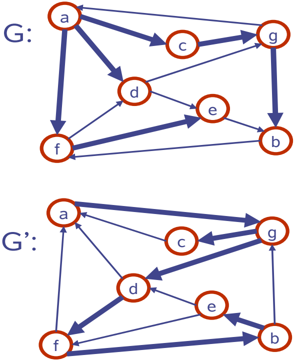
Strong Connectivity

- Each vertex can reach all other vertices



Strong Connectivity Algorithm

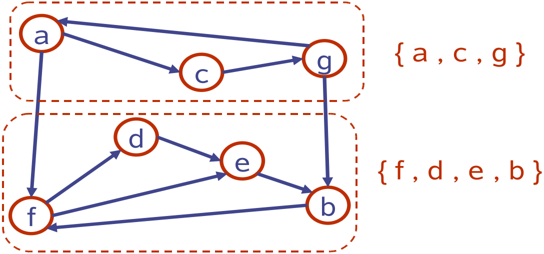
- Pick a vertex v in G.
- Perform a DFS from v in G.
  - If there's a w not visited, print "no".
- Let G' be G with edges reversed.
- Perform a DFS from v in G'.
  - If there's a w not visited, print "no".
  - Else, print "yes".



- Running time: O(n+m).

Strongly Connected Components

- Maximal subgraphs such that each vertex can reach all other vertices in the subgraph
- Can also be done in O(n+m) time using DFS, but is more complicated (similar to biconnectivity).



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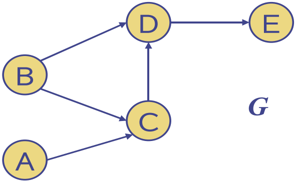
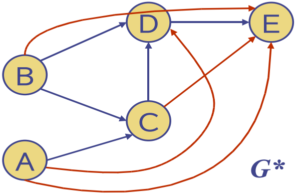
Transitive Closure

- Given a digraph G, the transitive closure of G is the digraph G^* such that
  - G^* has the same vertices as G
  - if G has a directed path from u to v ($u \neq v$), G^* has a directed edge from u to v
- The transitive closure provides reachability information about a digraph





Computing the Transitive Closure

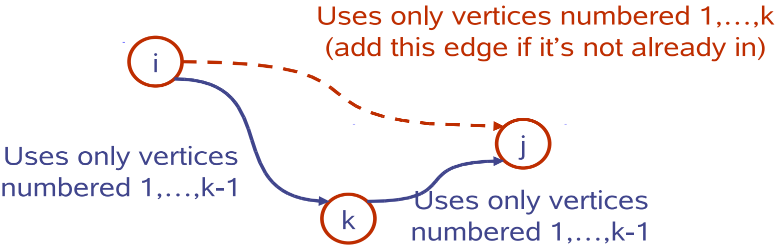
- We can perform DFS starting at each vertex
  - O(n(n+m))

If there's a way to get from A to B and from B to C, then there's a way to get from A to C.

- Alternatively ... Use dynamic programming: the Floyd-Warshall Algorithm

Floyd-Warshall Transitive Closure

- Idea #1: Number the vertices 1, 2, …, n.
- Idea #2: Consider paths that use only vertices numbered 1, 2, …, k, as intermediate vertices:

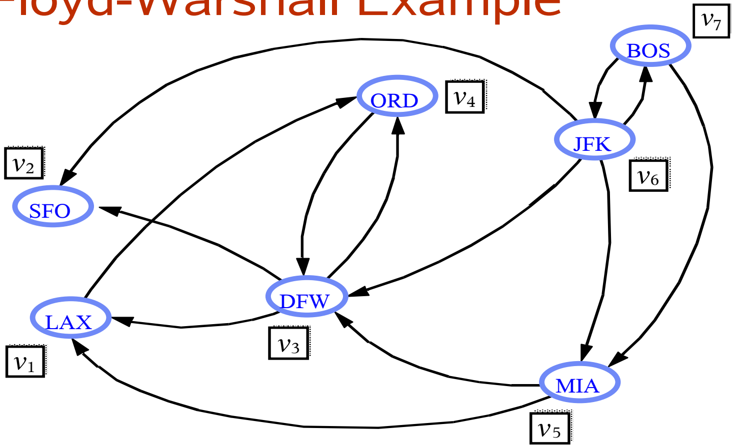


Floyd-Warshall's Algorithm

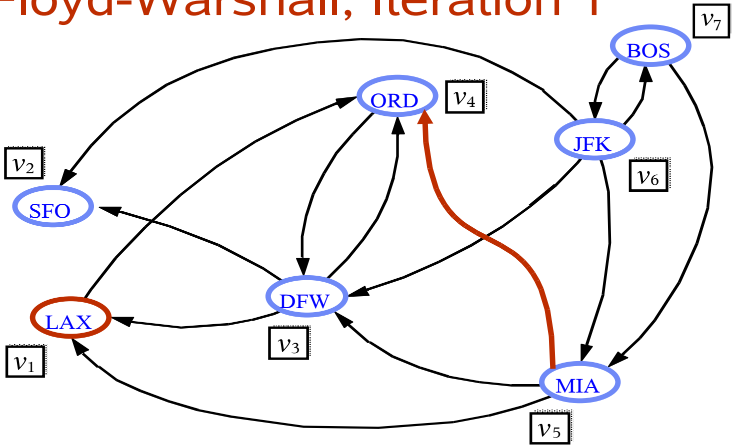
- Floyd-Warshall's algorithm numbers the vertices of G as $v_1, \ldots, v_n$ and computes a series of digraphs $G_0, \ldots, G_n$
  - $G_0 = G$
  - G_k has a directed edge (v_i, v_j) if G has a directed path from v_i to v_j with intermediate vertices in the set $\{v_1, \ldots, v_k\}$
- We have that $G_n = G^*$
- In phase k, digraph G_k is computed from G_{k-1}
- Running time: O(n³), assuming areAdjacent is O(1) (e.g., adjacency matrix)

```
Algorithm FloydWarshall(G)
  Input digraph G
  Output transitive closure G* of G
  i ← 1
  for all v ∈ G.vertices()
    denote v as v_i
    i ← i + 1
  G_0 ← G
  for k ← 1 to n do
    G_k ← G_{k−1}
     for i ← 1 to n (i ≠ k) do
       for j ← 1 to n (j ≠ i, k) do
          if G_{k−1}.areAdjacent(v_i, v_k) ∧
                G_{k−1}.areAdjacent(v_k, v_j)
             if ¬G_k.areAdjacent(v_i, v_j)
                G_k.insertDirectedEdge(v_i, v_j, k)
    return G_n
```

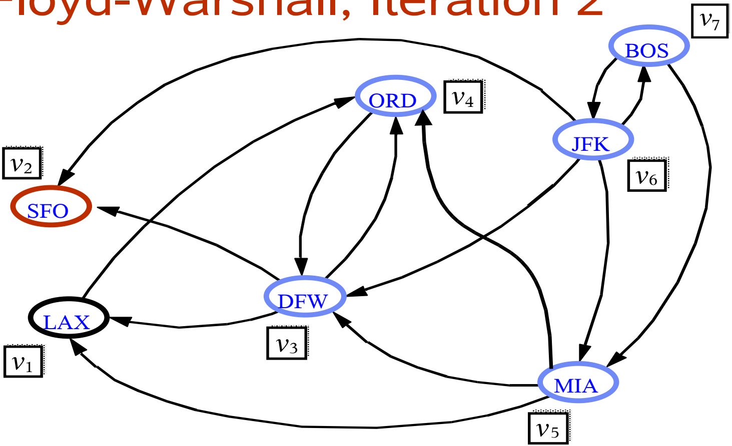
Floyd-Warshall Example



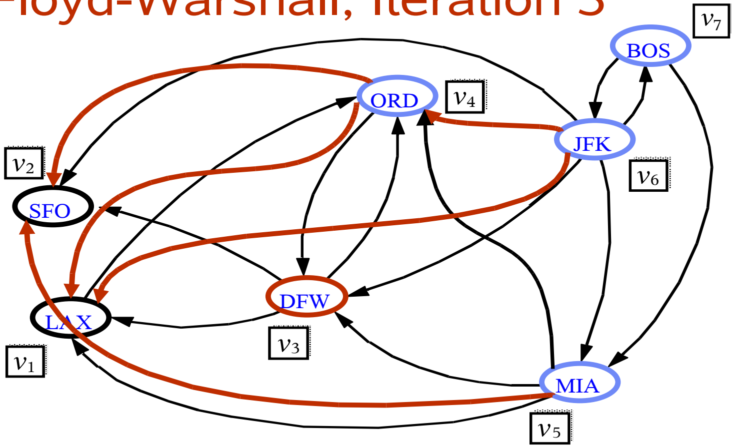
Floyd-Warshall, Iteration 1



Floyd-Warshall, Iteration 2



Floyd-Warshall, Iteration 3



Floyd-Warshall, etc...

Outline

DAGs and Topological Ordering

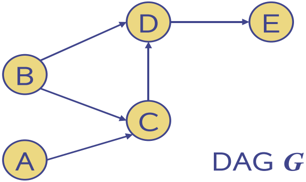
- A directed acyclic graph (DAG) is a digraph that has no directed cycles
- A topological ordering of a digraph is a numbering

  $$v_1, \ldots, v_n$$

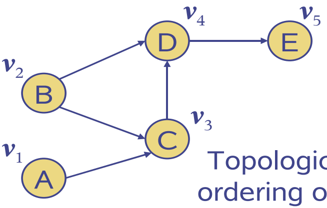
  of the vertices such that for every edge (v_i, v_j), we have $i < j$
- Example: in a task scheduling digraph, a topological ordering a task sequence that satisfies the precedence constraints

Theorem

A digraph admits a topological ordering if and only if it is a DAG



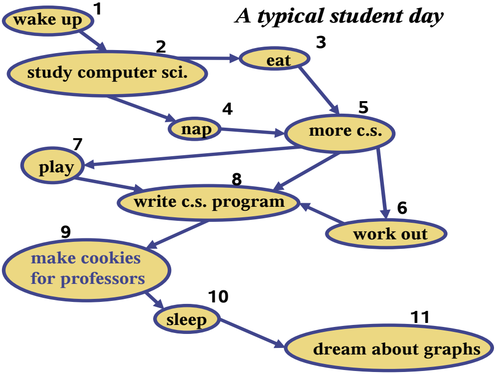
DAG G



Topological ordering of G

Topological Sorting

- Number vertices, so that (u,v) in E implies u < v



Algorithm for Topological Sorting

- Note: This algorithm is different than the one in Goodrich-Tamassia

```
Method TopologicalSort(G)
    H ← G            // Temporary copy of G
    n ← G.numVertices()
    while H is not empty do
        Let v be a vertex with no outgoing edges
        Label v ← n
        n ← n - 1
        Remove v from H
```

- Running time: O(n + m). How…?

Topological Sorting Algorithm using DFS

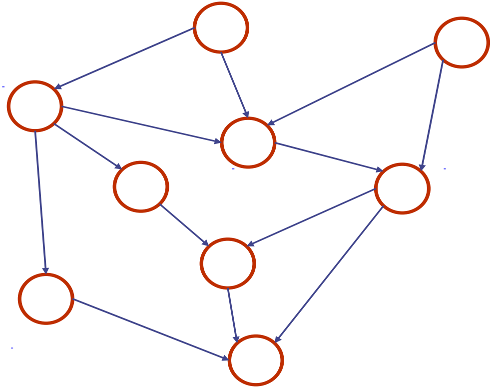
- Simulate the algorithm by using depth-first search

Algorithm *topologicalDFS*(*G*)
  Input dag *G*
  Output topological ordering of *G*
 n ← *G.numVertices*()
 for all *u* ∈ *G.vertices*()
  setLabel(*u, UNEXPLORED*)
 for all *e* ∈ *G.edges*()
  setLabel(*e, UNEXPLORED*)
 for all *v* ∈ *G.vertices*()
  if *getLabel*(*v*) = *UNEXPLORED*
   topologicalDFS(*G, v*)

- O(n+m) time.

Algorithm *topologicalDFS*(*G, v*)
  Input graph *G* and a start vertex *v* of *G*
  Output labeling of the vertices of *G* in the connected component of *v*
 setLabel(*v, VISITED*)
 for all *e* ∈ *G.incidentEdges*(*v*)
  if *getLabel*(*e*) = *UNEXPLORED*
   w ← *opposite*(*v,e*)
   if *getLabel*(*w*) = *UNEXPLORED*
    setLabel(*e, DISCOVERY*)
    topologicalDFS(*G, w*)
   else
    {*e* is a forward or cross edge}
 Label *v* with topological number *n*
 n ← *n* - 1

Topological Sorting Example



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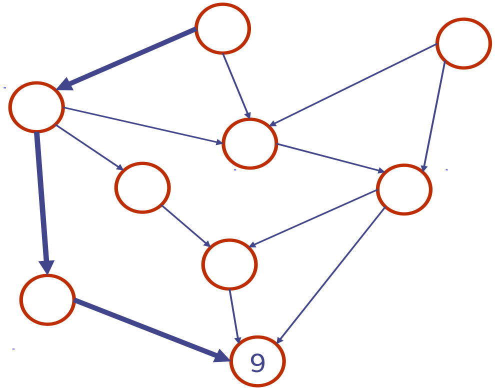

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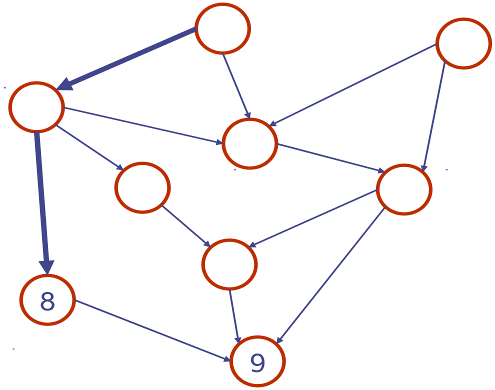

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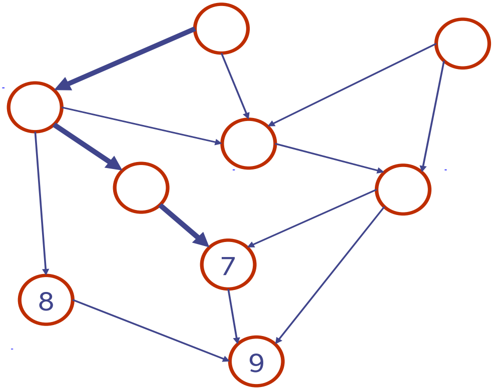

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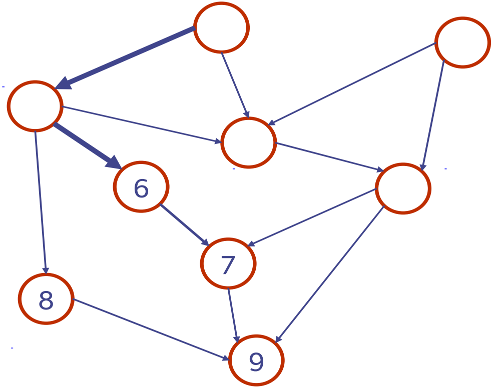
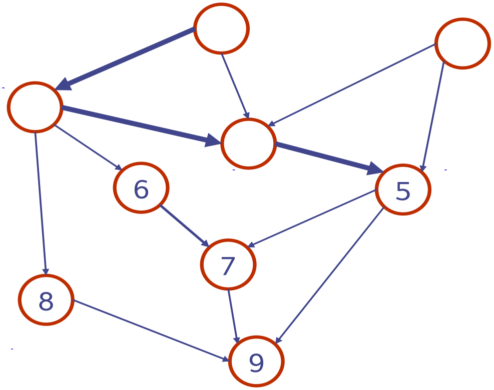


Topological Sorting Example



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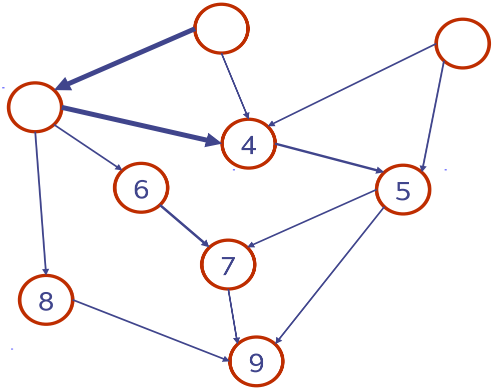

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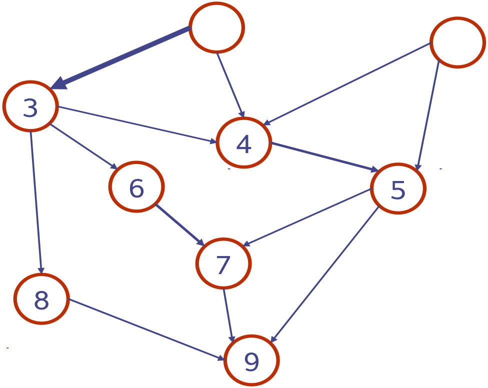

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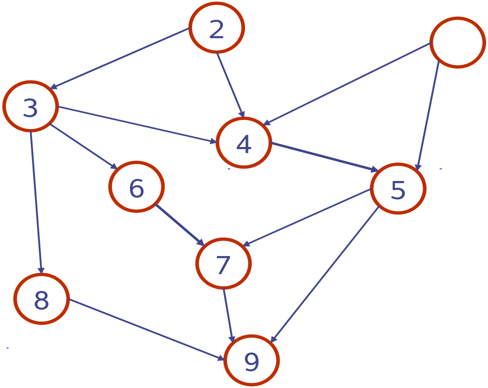

Topological Sorting Example