COMP9024: Data Structures and Algorithms

Week Eleven: Graphs (I)

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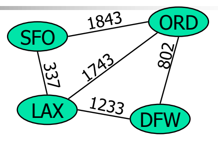
Outline

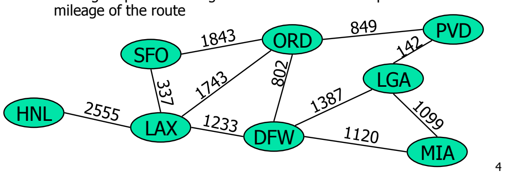
- Undirected Graphs and Directed Graphs
- Depth-First Search
- Breadth-First Search
- Transitive Closure
- Topological Sorting

Graphs



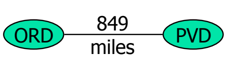
Graphs

- A graph is a pair (V, E), where
  - V is a set of nodes, called vertices
  - E is a collection of pairs of vertices, called edges
  - Vertices and edges are positions and store elements
- Example:
  - A vertex represents an airport and stores the three-letter airport code
  - An edge represents a flight route between two airports and stores the mileage of the route



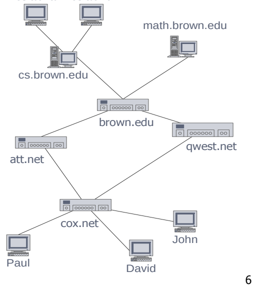
Edge Types

- Directed edge
  - ordered pair of vertices (u,v)
  - first vertex u is the origin
  - second vertex v is the destination
  - e.g., a flight
- Undirected edge
  - unordered pair of vertices (u,v)
  - e.g., a flight route
- Directed graph
  - all the edges are directed
  - e.g., route network
- Undirected graph
  - all the edges are undirected
  - e.g., flight network



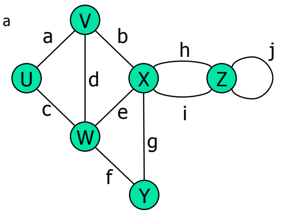
Applications

- Electronic circuits
  - Printed circuit board
  - Integrated circuit
- Transportation networks
  - Highway network
  - Flight network
- Computer networks
  - Local area network
  - Internet
  - Web
- Databases
  - Entity-relationship diagram



Terminology (1/3)

- End vertices (or endpoints) of an edge
  - U and V are the endpoints of a
- Edges incident on a vertex
  - a, d, and b are incident on V
- Adjacent vertices
  - U and V are adjacent
- Degree of a vertex
  - X has degree 5
- Parallel edges
  - h and i are parallel edges
- Self-loop
  - j is a self-loop



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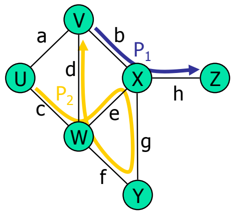
Terminology (2/3)

- Path
  - sequence of alternating vertices and edges
  - begins with a vertex
  - ends with a vertex
  - each edge is preceded and followed by its endpoints
- Simple path
  - path such that all its vertices and edges are distinct
- Examples
  - P_1=(V,b,X,h,Z) is a simple path
  - P_2=(U,c,W,e,X,g,Y,f,W,d,V) is a path that is not simple



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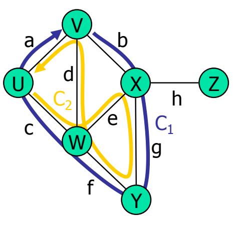
Terminology (3/3)

- Cycle
  - circular sequence of alternating vertices and edges
  - each edge is preceded and followed by its endpoints
- Simple cycle
  - cycle such that all its vertices and edges are distinct
- Examples
  - C_1=(V,b,X,g,Y,f,W,c,U,a,↵) is a simple cycle
  - C_2=(U,c,W,e,X,g,Y,f,W,d,V,a,↵) is a cycle that is not simple



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Properties

Property 1

$\sum_v \deg(v) = 2m$

Proof: each edge is counted twice

Property 2

In an undirected graph with no self-loops and no multiple edges

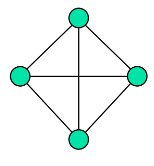
$m \le n(n-1)/2$

Proof: each vertex has degree at most $(n-1)$

What is the bound for a directed graph?

Notation

n	number of vertices
m	number of edges
$\deg(v)$	degree of vertex v



Example

- $n = 4$
- $m = 6$
- $\deg(v) = 3$

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Main Methods of the Graph ADT

- Vertices and edges
  - are positions
  - store elements
- Accessor methods
  - endVertices(e): an array of the two endvertices of e
  - opposite(v, e): the vertex opposite of v on e
  - areAdjacent(v, w): true iff v and w are adjacent
  - replace(v, x): replace element at vertex v with x
  - replace(e, x): replace element at edge e with x
- Update methods
  - insertVertex(o): insert a vertex storing element o
  - insertEdge(v, w, o): insert an edge (v,w) storing element o
  - removeVertex(v): remove vertex v (and its incident edges)
  - removeEdge(e): remove edge e
- Iterator methods
  - incidentEdges(v): edges incident to v
  - vertices(): all vertices in the graph
  - edges(): all edges in the graph

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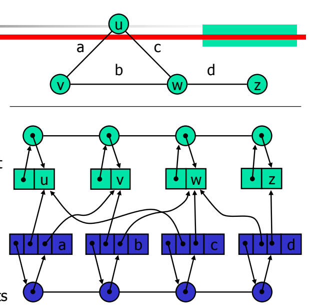
Edge List Structure

- Vertex object
  - element
  - reference to position in vertex sequence
- Edge object
  - element
  - origin vertex object
  - destination vertex object
  - reference to position in edge sequence
- Vertex sequence
  - sequence of vertex objects
- Edge sequence
  - sequence of edge objects



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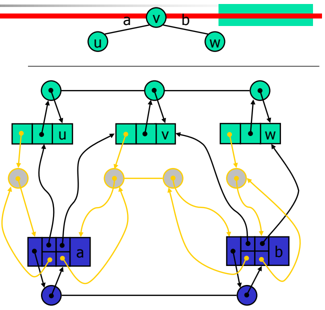
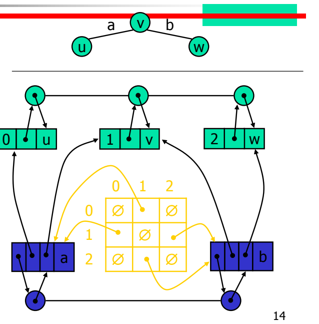
Adjacency List Structure

- Edge list structure
- Incidence sequence for each vertex
  - sequence of references to edge objects of incident edges
- Augmented edge objects
  - references to associated positions in incidence sequences of end vertices



Adjacency Matrix Structure

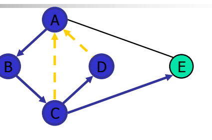
- Edge list structure
- Augmented vertex objects
  - Integer key (index) associated with vertex
- 2D-array adjacency array
  - Reference to edge object for adjacent vertices
  - Null for non nonadjacent vertices
- The "old fashioned" version just has 0 for no edge and 1 for edge



Asymptotic Performance

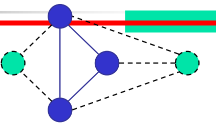
▪ n vertices, m edges ▪ no parallel edges ▪ no self-loops ▪ Bounds are "big-Oh"	Edge List	Adjacency List	Adjacency Matrix
Space	$n + m$	$n + m$	n^2
incidentEdges(v)	m	deg(v)	n
areAdjacent (v, w)	m	min(deg(v), deg(w))	1
insertVertex(o)	1	1	n^2
insertEdge(v, w, o)	1	1	1
removeVertex(v)	m	deg(v)	n^2
removeEdge(e)	1	1	1

Depth-First Search

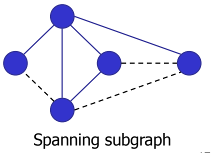


Subgraphs

- A subgraph S of a graph G is a graph such that
  - The vertices of S are a subset of the vertices of G
  - The edges of S are a subset of the edges of G
- A spanning subgraph of G is a subgraph that contains all the vertices of G



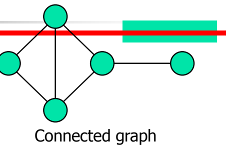
Subgraph



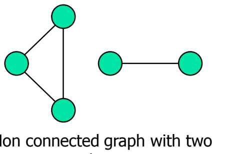
Spanning subgraph

Connectivity

- A graph is connected if there is a path between every pair of vertices
- A connected component of a graph G is a maximal connected subgraph of G



Connected graph

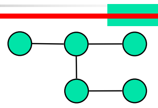


Non connected graph with two connected components

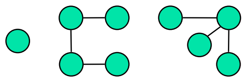
Trees and Forests

- A (free) tree is an undirected graph T such that
  - T is connected
  - T has no cycles

  This definition of tree is different from the one of a rooted tree
- A forest is an undirected graph without cycles
- The connected components of a forest are trees



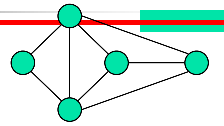
Tree



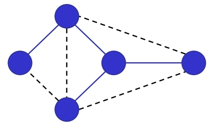
Forest

Spanning Trees and Forests

- A spanning tree of a connected graph is a spanning subgraph that is a tree
- A spanning tree is not unique unless the graph is a tree
- Spanning trees have applications to the design of communication networks
- A spanning forest of a graph is a spanning subgraph that is a forest



Graph



Spanning tree

Depth-First Search

- Depth-first search (DFS) is a general technique for traversing a graph
- A DFS traversal of a graph G
  - Visits all the vertices and edges of G
  - Determines whether G is connected
  - Computes the connected components of G
  - Computes a spanning forest of G
- DFS on a graph with n vertices and m edges takes $O(n + m)$ time
- DFS can be further extended to solve other graph problems
  - Find and report a path between two given vertices
  - Find a cycle in the graph
- Depth-first search is to graphs what Euler tour is to binary trees

DFS Algorithm

- The algorithm uses a mechanism for setting and getting "labels" of vertices and edges

```
Algorithm DFS(G)
    Input graph G
    Output labeling of the edges of G
        as discovery edges and
        back edges
{ 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 )
          DFS(G, v);
}
```

```
Algorithm DFS(G, v)
    Input graph G and a start vertex v of G
    Output labeling of the edges of G
        in the connected component of v
        as discovery edges and back edges
{ setLabel(v, VISITED);
  for all e ∈ G.incidentEdges(v)
      if ( getLabel(e) = UNEXPLORED )
        { w = opposite(v, e);
          if ( getLabel(w) = UNEXPLORED )
            { setLabel(e, DISCOVERY);
              DFS(G, w);
            }
          else
              setLabel(e, BACK);
        }
}
```


Example (1/2)

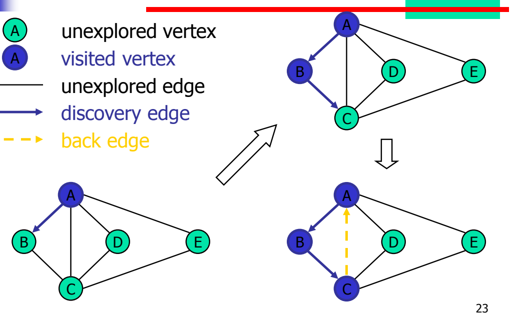
A unexplored vertex

A visited vertex

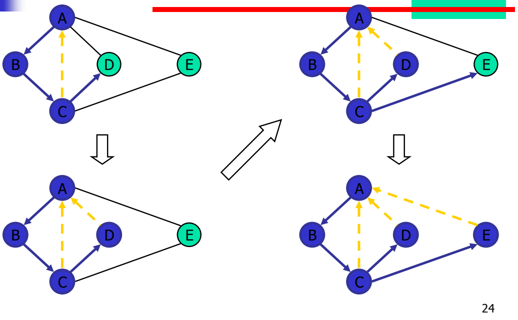
unexplored edge

discovery edge

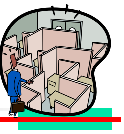
back edge



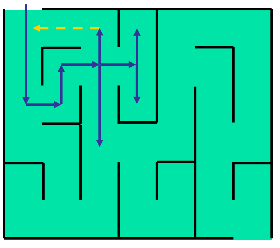
Example (2/2)



DFS and Maze Traversal



- The DFS algorithm is similar to a classic strategy for exploring a maze
  - We mark each intersection, corner and dead end (vertex) visited
  - We mark each corridor (edge) traversed
  - We keep track of the path back to the entrance (start vertex) by means of a rope (recursion stack)



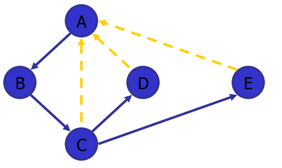
Properties of DFS

Property 1

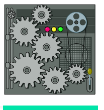
DFS(*G*, *v*) visits all the vertices and edges in the connected component of *v*

Property 2

The discovery edges labeled by *DFS*(*G*, *v*) form a spanning tree of the connected component of *v*



Analysis of DFS



- Setting/getting a vertex/edge label takes $O(1)$ time
- Each vertex is labeled twice
  - once as UNEXPLORED
  - once as VISITED
- Each edge is labeled twice
  - once as UNEXPLORED
  - once as DISCOVERY or BACK
- Method incidentEdges is called once for each vertex
- DFS runs in $O(n + m)$ time provided the graph is represented by the adjacency list structure
  - Recall that $\Sigma_v \deg(v) = 2m$

Path Finding

- We can specialize the DFS algorithm to find a path between two given vertices *v* and *z* using the template method pattern
- We call *DFS*(*G*, *v*) with *v* as the start vertex
- We use a stack *S* to keep track of the path between the start vertex and the current vertex
- As soon as destination vertex *z* is encountered, we return the path as the contents of the stack

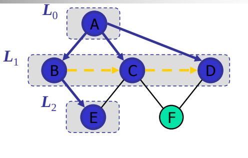
```
Algorithm pathDFS(G, v, z)
 { setLabel(v, VISITED);
   S.push(v);
   if ( v = z )
     return S.elements();
   for all  e ∈ G.incidentEdges(v)
     if ( getLabel(e) = UNEXPLORED )
      { w = opposite(v,e);
        if ( getLabel(w) = UNEXPLORED )
          { setLabel(e, DISCOVERY);
            S.push(e);
            pathDFS(G, w, z);
            S.pop(e);
          }
        else
          setLabel(e, BACK);
      }
   S.pop(v);
 }
```


Cycle Finding

- We can specialize the DFS algorithm to find a simple cycle using the template method pattern
- We use a stack *S* to keep track of the path between the start vertex and the current vertex
- As soon as a back edge (*v*, *w*) is encountered, we return the cycle as the portion of the stack from the top to vertex *w*

```
Algorithm cycleDFS(G, v, z)
 { setLabel(v, VISITED);
   S.push(v);
   for all  e ∈ G.incidentEdges(v)
     if ( getLabel(e) = UNEXPLORED )
      { w = opposite(v,e);
        S.push(e);
        if ( getLabel(w) = UNEXPLORED )
          { setLabel(e, DISCOVERY);
            pathDFS(G, w, z);
            S.pop(e); }
        else
          { T = new empty stack
            repeat
              { o = S.pop();
                T.push(o); }
            until ( o = w );
            return T.elements();  }
   S.pop(v);
 }
```


Breadth-First Search



Breadth-First Search

- Breadth-first search (BFS) is a general technique for traversing a graph
- A BFS traversal of a graph G
  - Visits all the vertices and edges of G
  - Determines whether G is connected
  - Computes the connected components of G
  - Computes a spanning forest of G
- BFS on a graph with n vertices and m edges takes $O(n + m)$ time
- BFS can be further extended to solve other graph problems
  - Find and report a path with the minimum number of edges between two given vertices
  - Find a simple cycle, if there is one

BFS Algorithm

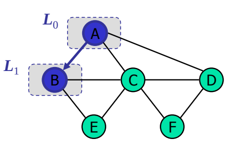
- The algorithm uses a mechanism for setting and getting "labels" of vertices and edges

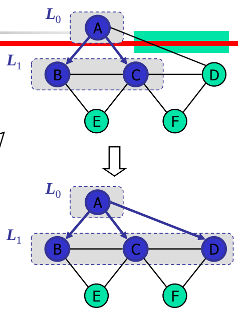
```
Algorithm BFS(G)
    Input graph G
    Output labeling of the edges
        and partition of the
        vertices of G
  {
   for all u ∈ G.vertices()
     setLabel(u, UNEXPLORED);
   for all e ∈ G.edges()
     setLabel(e, UNEXPLORED);
   for all v ∈ G.vertices()
     if ( getLabel(v) = UNEXPLORED )
        BFS(G, v);
  }
```

```
Algorithm BFS(G, s)
 { L0 = new empty sequence;
   L0.insertLast(s);
   setLabel(s, VISITED);
   i = 0;
   while ( ¬Li.isEmpty() )
    { Li+1 = new empty sequence;
      for all v ∈ Li.elements()
        for all e ∈ G.incidentEdges(v)
          if ( getLabel(e) = UNEXPLORED )
           { w = opposite(v,e);
             if ( getLabel(w) = UNEXPLORED )
              { setLabel(e, DISCOVERY);
                setLabel(w, VISITED);
                Li+1.insertLast(w); }
             else
                setLabel(e, CROSS);
           }
      i = i +1;
    }
 }
```

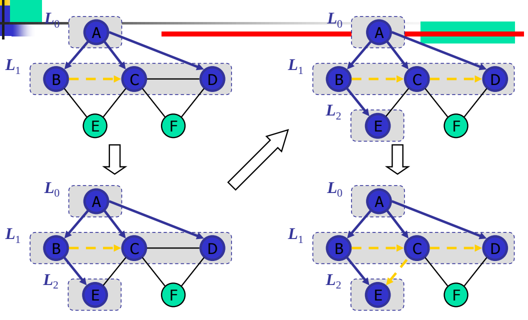

Example (1/3)

- A unexplored vertex
- A visited vertex
- unexplored edge
- discovery edge
- cross edge

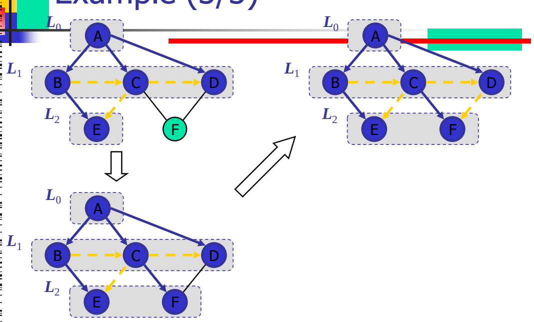




Example (2/3)



Example (3/3)



Properties

Notation

G_s: connected component of s

Property 1

$BFS(G, s)$ visits all the vertices and edges of G_s

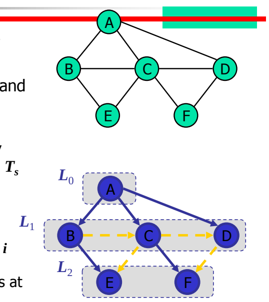
Property 2

The discovery edges labeled by $BFS(G, s)$ form a spanning tree T_s of G_s

Property 3

For each vertex v in L_i

- The path of T_s from s to v has i edges
- Every path from s to v in G_s has at least i edges



Analysis

- Setting/getting a vertex/edge label takes $O(1)$ time
- Each vertex is labeled twice
  - once as UNEXPLORED
  - once as VISITED
- Each edge is labeled twice
  - once as UNEXPLORED
  - once as DISCOVERY or CROSS
- Each vertex is inserted once into a sequence L_i
- Method incidentEdges is called once for each vertex
- BFS runs in $O(n + m)$ time provided the graph is represented by the adjacency list structure
  - Recall that $\sum_v \deg(v) = 2m$

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Applications

- Using the template method pattern, we can specialize the BFS traversal of a graph G to solve the following problems in $O(n + m)$ time
  - Compute the connected components of G
  - Compute a spanning forest of G
  - Find a simple cycle in G, or report that G is a forest
  - Given two vertices of G, find a path in G between them with the minimum number of edges, or report that no such path exists

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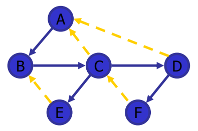
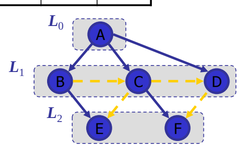
DFS vs. BFS (1/2)

Applications	DFS	BFS
Spanning forest, connected components, paths, cycles	√	√
Shortest paths		√
Biconnected components	√	



DFS



BFS

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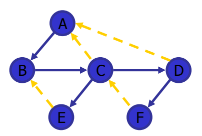
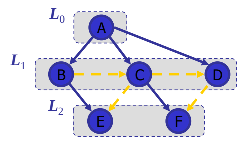
DFS vs. BFS (2/2)

Back edge (v,w)
- w is an ancestor of v in the tree of discovery edges

Cross edge (v,w)
- w is in the same level as v or in the next level in the tree of discovery edges



DFS



BFS

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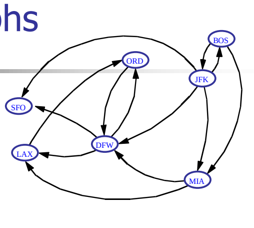
Directed Graphs



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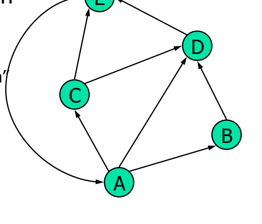
Digraphs

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



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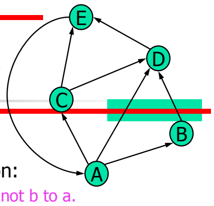
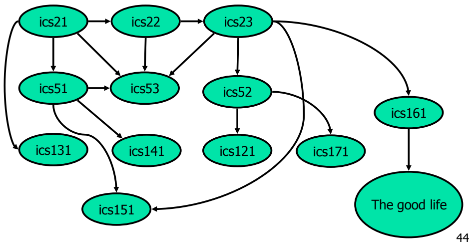
Digraph Properties



- 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 in-edges and out-edges in time proportional to their size.

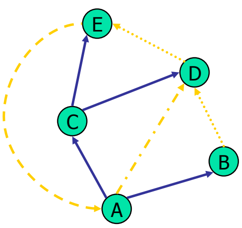
Digraph Application

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

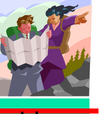


Directed DFS

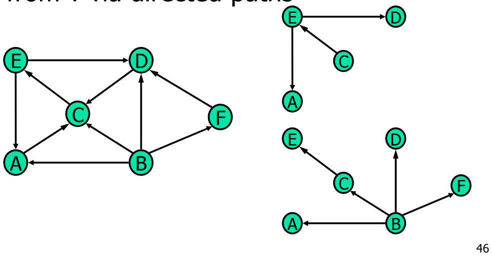
- We can specialize the traversal algorithms (DFS and BFS) to digraphs by traversing edges only along their direction
- In the directed DFS algorithm, we have four types of edges
  - discovery edges
  - back edges
  - forward edges
  - cross edges
- A directed DFS starting a a vertex *s* determines the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



Reachability

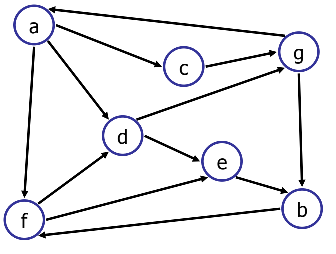


- DFS tree rooted at v: vertices reachable from v via directed paths



Strong Connectivity

- Each vertex can reach all other vertices

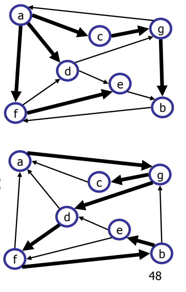


Strong Connectivity Algorithm

- 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).

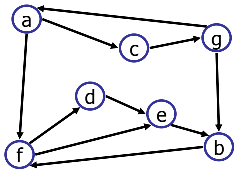
G:

G':



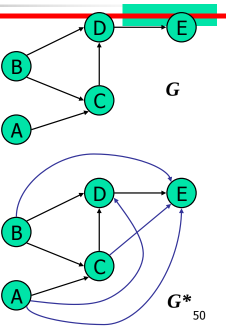
Strongly Connected Components

- 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).



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



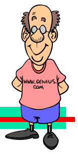
Computing the Transitive Closure

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

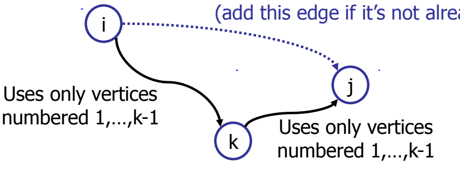
If there's a way to get from A to B and from B to C, then there's a way to get from A to C.

◆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:

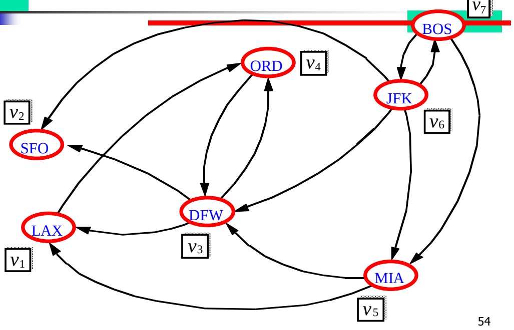


Floyd-Warshall's Algorithm

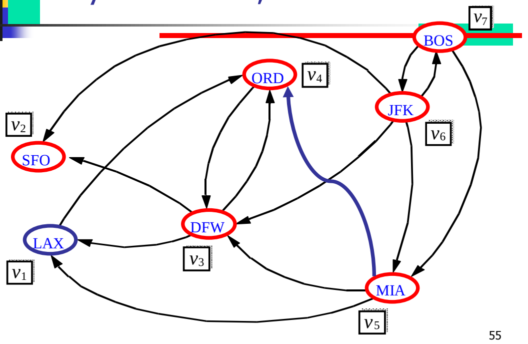
- Floyd-Warshall's algorithm numbers the vertices of G as $v_1, \ldots, v_n$ and computes a series of digraphs $G_0, \ldots, G_n$
  - $G_0 = G$
  - G_k has a directed edge (v_i, v_j) if G has a directed path from v_i to v_j with intermediate vertices in the set $\{v_1, \ldots, v_k\}$
- We have that $G_n = G^*$
- In phase k, digraph G_k is computed from G_{k-1}
- Running time: O(n^3), 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



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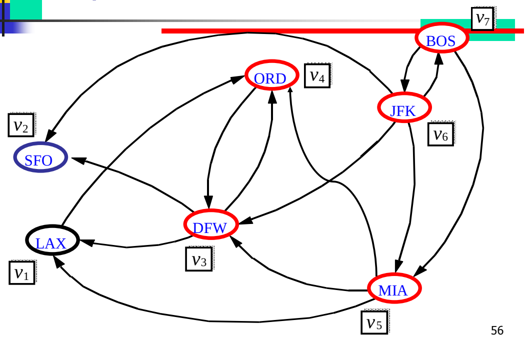
Floyd-Warshall, Iteration 2



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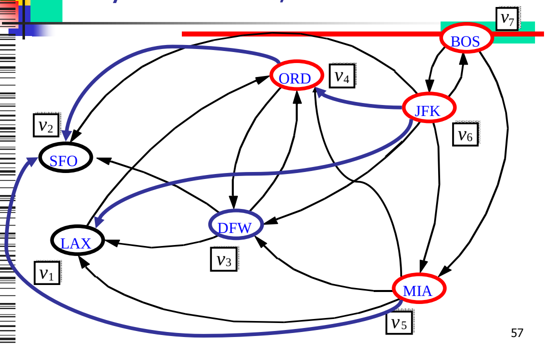
Floyd-Warshall, Iteration 3



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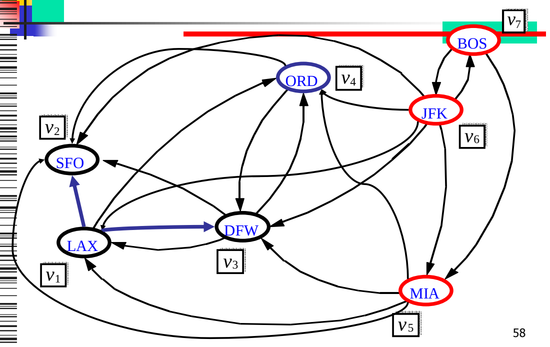
Floyd-Warshall, Iteration 4



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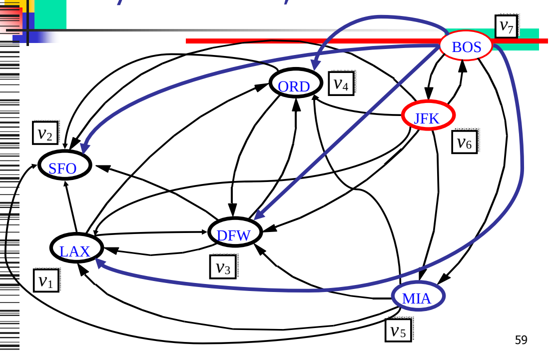
Floyd-Warshall, Iteration 5



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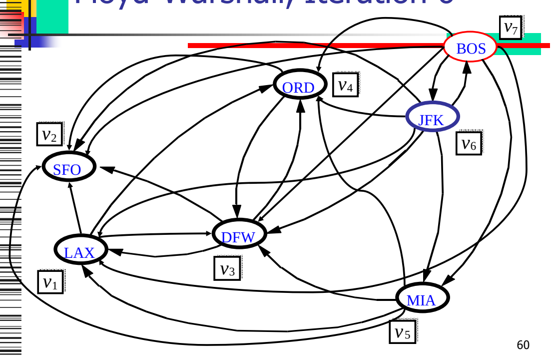
Floyd-Warshall, Iteration 6



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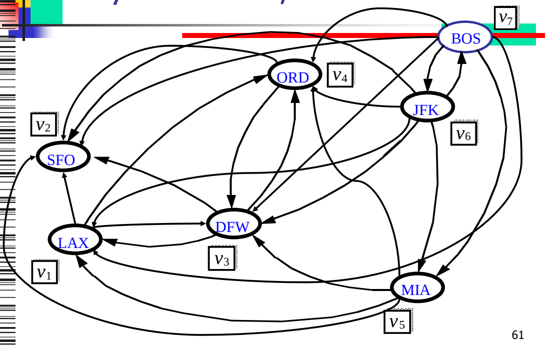
Floyd-Warshall, Conclusion



DAGs and Topological Ordering

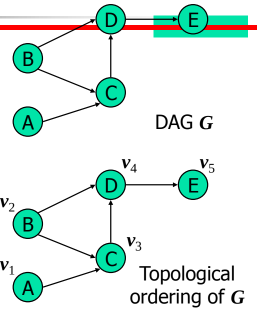
- A directed acyclic graph (DAG) is a digraph that has no directed cycles
- A topological ordering of a digraph is a numbering

  $v_1, \ldots, v_n$

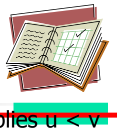
  of the vertices such that for every edge (v_i, v_j), we have $i < j$
- Example: in a task scheduling digraph, a topological ordering a task sequence that satisfies the precedence constraints

Theorem

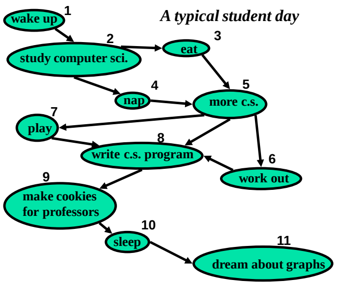
A digraph admits a topological ordering if and only if it is a DAG



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

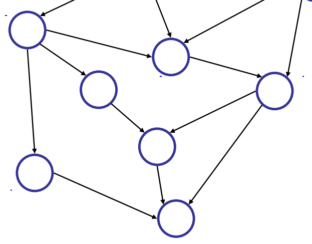
- Simulate the algorithm by using depth-first search

```
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);
}
```

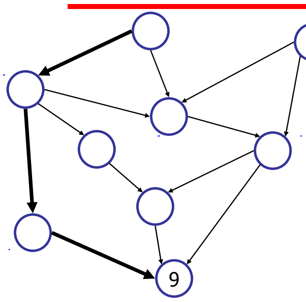
```
Algorithm topologicalDFS(G, v)
   Input graph G and a start vertex v of G
   Output labeling of the vertices of G
      in the connected component of v
{ setLabel(v, VISITED);
  for all e ∈ G.incidentEdges(v)
     if ( getLabel(e) = UNEXPLORED )
       { w = opposite(v,e);
         if ( getLabel(w) = UNEXPLORED )
           { setLabel(e, DISCOVERY);
             topologicalDFS(G, w); }
       }
   Label v with topological number n;
   n = n – 1;
   return;
}
```

- O(n+m) time.

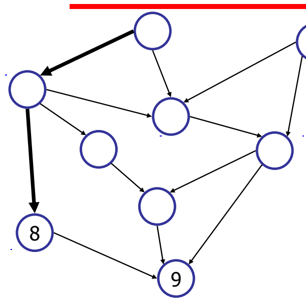
Topological Sorting Example (1/10)



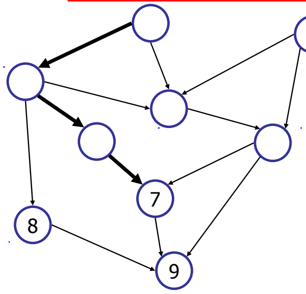
Topological Sorting Example (2/10)



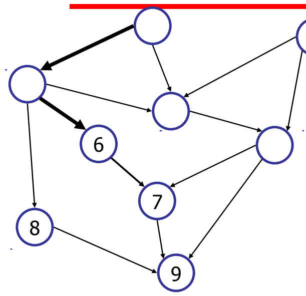
Topological Sorting Example (3/10)



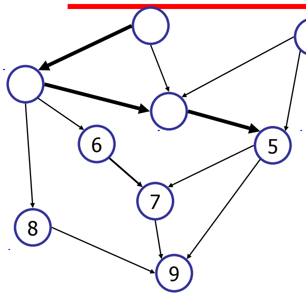
Topological Sorting Example (4/10)



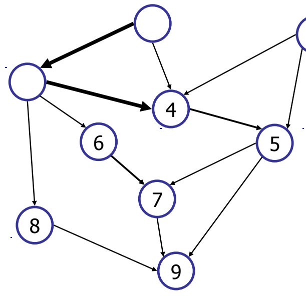
Topological Sorting Example (5/10)



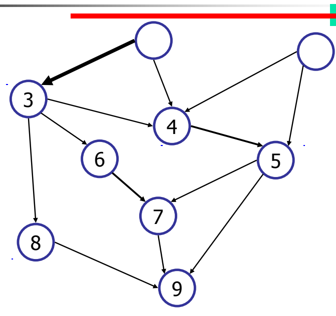
Topological Sorting Example (6/10)



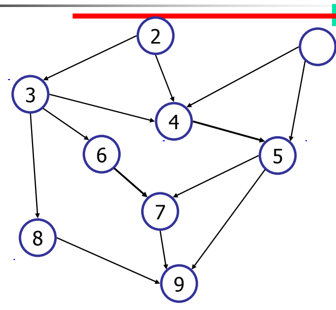
Topological Sorting Example (7/10)



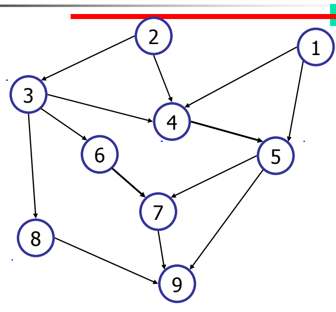
Topological Sorting Example (8/10)



Topological Sorting Example (9/10)



Topological Sorting Example (10/10)



References

1. Chapter 13, Data Structures and Algorithms by Goodrich and Tamassia.