Data Structures and Algorithms

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- Week 08 -

B.S. In Applied Computer Science
Free University of Bozen/Bolzano
academic year 2010-2011

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Data Structures and Algorithms
Week 8

1. Graphs – principles
2. Graph representations
3. Traversing graphs
   - Breadth-First Search
   - Depth-First Search
4. DAGs and Topological Sorting

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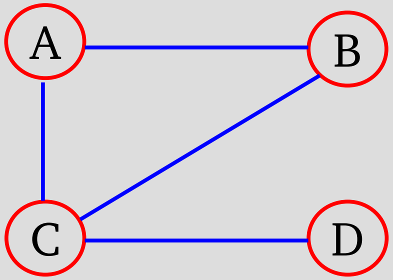
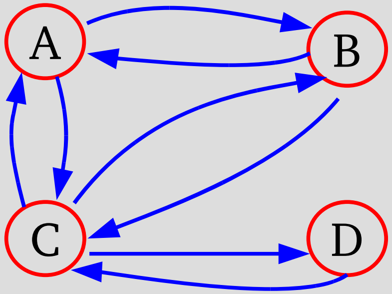
Graphs – Definition

- A **graph G = (V,E)** is composed of:
  - V: set of **vertices**
  - $E \subset V \times V$: set of **edges** connecting the **vertices**
- An **edge** ***e*** = (u,v) is a pair of vertices
- We assume **directed** graphs.
  - If a graph is undirected, we represent an edge between u and v by having $(u,v) \in E$ and $(v,u) \in E$





V = {A, B, C, D}

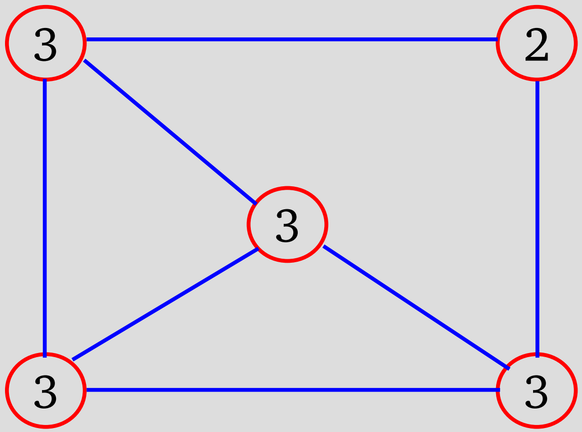
E = {(A,B), (B,A), (A,C), (C,A), (C,D), (D,C), (B,C), (C,B)}

Applications

- Electronic circuits, pipeline networks
- Transportation and communication networks
- Modeling any sort of relationtionships (between components, people, processes, concepts)

Graph Terminology

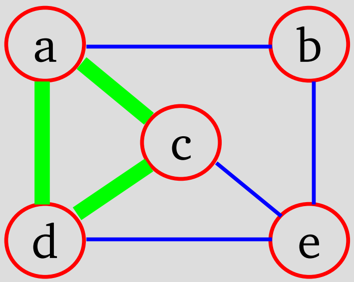
- Vertex v is **adjacent** to vertex u iff $(u,v) \in E$
- **degree** of a **vertex**: # of adjacent vertices



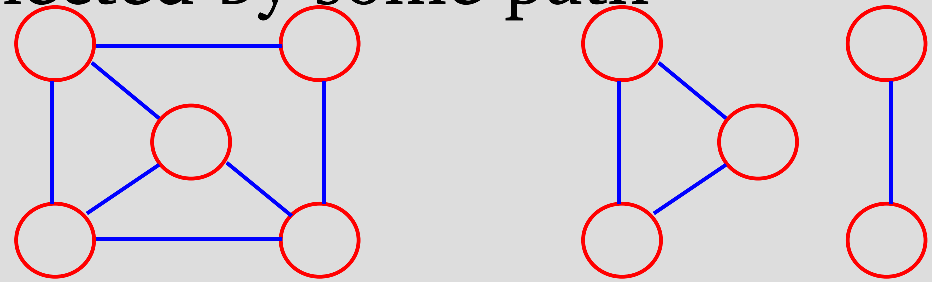
- **Path** – a sequence of vertices $v_1, v_2, \ldots v_k$ such that v_{i+1} is adjacent to v_i for $i = 1 .. k - 1$

Graph Terminology/2

- **Simple path** – a path with no repeated vertices

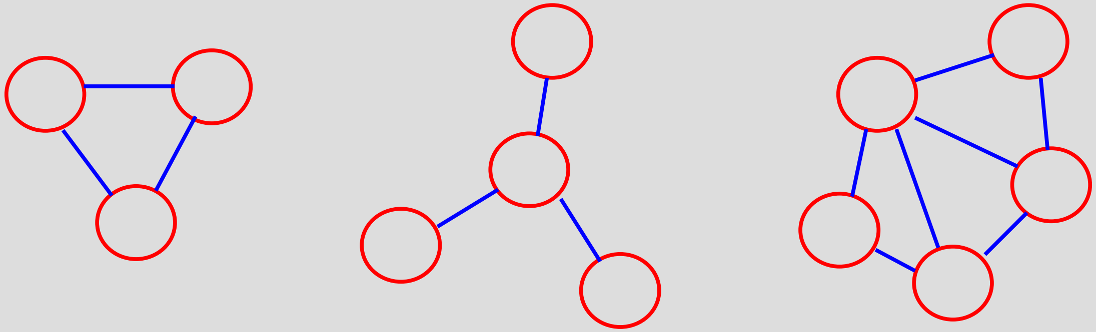


- **Cycle** – a simple path, except that the last vertex is the same as the first vertex
- **Connected** graph: any two vertices are connected by some path



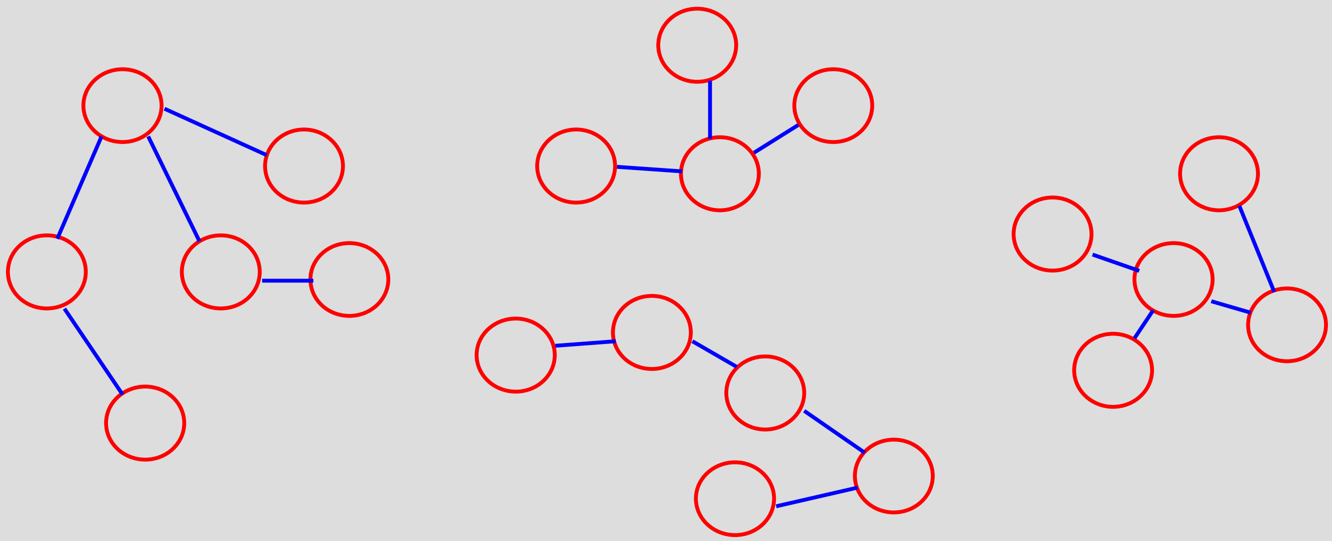
Graph Terminology/3

- **Subgraph** – a subset of vertices and edges forming a graph
- **Connected component** – maximal connected subgraph.
  - For example, the graph below has 3 connected components



Graph Terminology/4

- **tree** – connected graph without cycles
- **forest** – collection of trees



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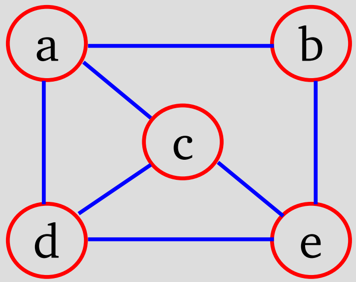
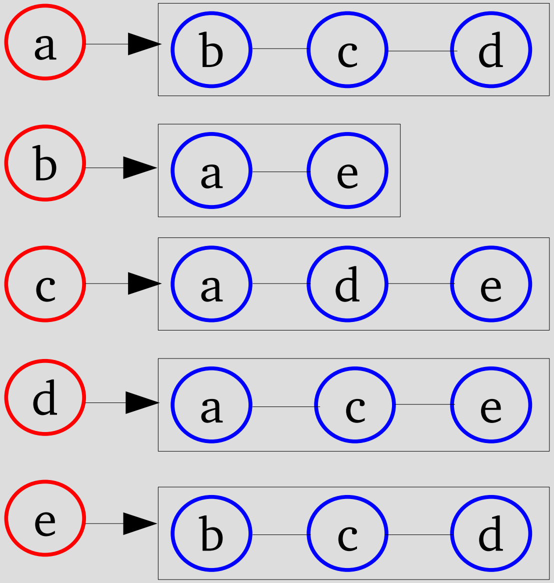
Data Structures for Graphs

- The **Adjacency list** of a vertex v: a sequence of vertices adjacent to v
- Represent the graph by the adjacency lists of all its vertices

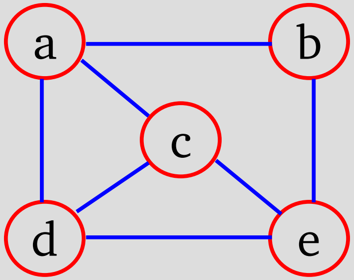




$$\text{Space } = \Theta(|V| + \sum \deg(v)) = \Theta(|V| + |E|)$$

Adjacency Matrix

- Matrix M with entries for all pairs of vertices
- M[i,j] = true – there is an edge (i,j) in the graph
- M[i,j] = false – there is no edge (i,j) in the graph
- Space = $O(|V|^2)$



	A	B	C	D	E
A	F	T	T	T	F
B	T	F	F	F	T
C	T	F	F	T	T
D	T	F	T	F	T
E	F	T	T	T	F

Pseudocode Assumptions

- Each node has some properties (fields of a record):
  - **adj**: list of adjacenced nodes
  - **dist**: distance from start node in a traversal
  - **pred**: predecessor in a traversal
  - **color**: color of the node (is changed during traversal; white, gray, black)
  - **starttime**: time when first visited during a traversal (depth first search)
  - **endtime**: time when last visited during a traversal (depth first search)

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Graph Searching Algorithms

- Systematic search of every edge and vertex of the graph
- Graph G = (V,E) is either directed or undirected
- Applications
  - Compilers
  - Graphics
  - Maze-solving
  - Networks: routing, searching, clustering, etc.

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Breadth First Search

- A **Breadth-First Search (BFS)** traverses a **connected component** of an (un)directed graph, and in doing so defines a **spanning tree**.
- BFS in an **undirected** graph G is like wandering in a labyrinth with a string and exploring the neighborhood first.
- The starting vertex *s*, it is assigned distance 0.
- In the first round the string is unrolled 1 unit. All edges that are 1 edge away from the anchor are visited (**discovered**) and assigned distance 1.

Breadth-First Search/2

- In the second round, all the new edges that can be reached by unrolling the string 2 edges are visited and assigned a distance of 2
- This continues until every vertex has been assigned a level
- The label of any vertex *v* corresponds to the length of the shortest path (in terms of edges) from *s* to *v*

BFS Algorithm

```
BFS(G,s)
for u ∈ G.V
   u.color := white
   u.dist := ∞
   u.pred := NIL
s.color := gray
s.dist := 0
init-queue(Q)
enqueue(Q,s) // FIFO queue
while not isEmpty(Q)
   u := head(Q)
   for v ∈ u.adj do
      if v.color = white then
         v.color := gray
         v.dist := u.dist + 1
         v.pred := u
         enqueue(Q,v)
   dequeue(Q)
   u.color := black
```

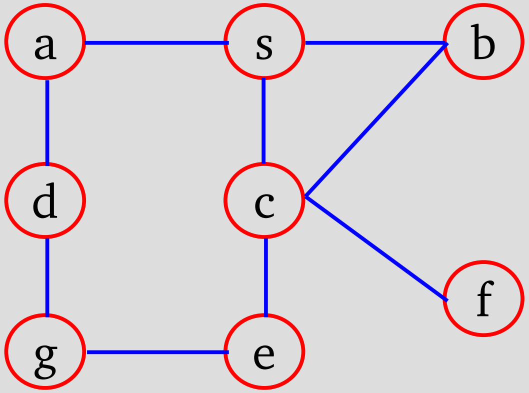
Init all vertices

Init BFS with s

Handle all of u's children before handling children of children

Coloring of Vertices

- A vertex is **white** if it is undiscovered
- A vertex is **gray** if it has been discovered but not all of its edges have been explored
- A vertex is **black** after all of its adjacent vertices have been discovered (the adj. list was examined completely)
- Lets do an example of BFS:



BFS Running Time

- Given a graph G = (V,E)
  - Vertices are enqueued if their color is white
  - Assuming that en- and dequeuing takes O(1) time the total cost of this operation is O(V)
  - Adjacency list of a vertex is scanned when the vertex is dequeued
  - The sum of the lengths of all lists is $\Theta(E)$. Thus, O(E) time is spent on scanning them.
  - Initializing the algorithm takes O(V)
- **Total running time O(V+E)** (linear in the size of the adjacency list representation of G)

BFS Properties

- Given a graph G = (V,E), BFS **discovers all vertices reachable from a source vertex *s***
- It computes the **shortest distance** to all reachable vertices
- It computes a **breadth-first tree** that contains all such reachable vertices
- For any vertex *v* reachable from *s*, the path in the breadth first tree from s to v, corresponds to a **shortest path** in G

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Depth-First Search

- **A depth-first search (DFS)** in an undirected graph G is like wandering in a labyrinth with a **string** and following one path to the end
  - We start at vertex *s*, tying the end of our string to the point and painting *s* "visited (discovered)". Next we label *s* as our current vertex called *u*
  - Now, we travel along an arbitrary edge (*u*,*v*).
  - If edge (*u*,*v*) leads us to an already visited vertex *v* we return to *u*.
  - If vertex *v* is unvisited, we unroll our string, move to *v*, paint *v* "visited", set *v* as our current vertex, and repeat the previous steps.

Depth-First Search/2

- Eventually, we will get to a point where **all edges from *u* lead to visited vertices**
- We then **backtrack** by rolling up our string until we get back to a previously visited vertex *v*.
- *v* becomes our current vertex and we repeat the previous steps

DFS Algorithm

```
DFS-All(G)
for u ∈ G.V
    u.color := white
    u.pred := NIL
time := 0
for u ∈ G.V
    if u.color = white then DFS(u)
```

Init all vertices

Visit all vertices

```
DFS(u)
u.color := gray
time := time + 1
u.starttime := time
for v ∈ u.adj
    if v.color = white then
        v.pred := u
        DFS(v)
u.color := black
time := time + 1
u.endtime := time
```

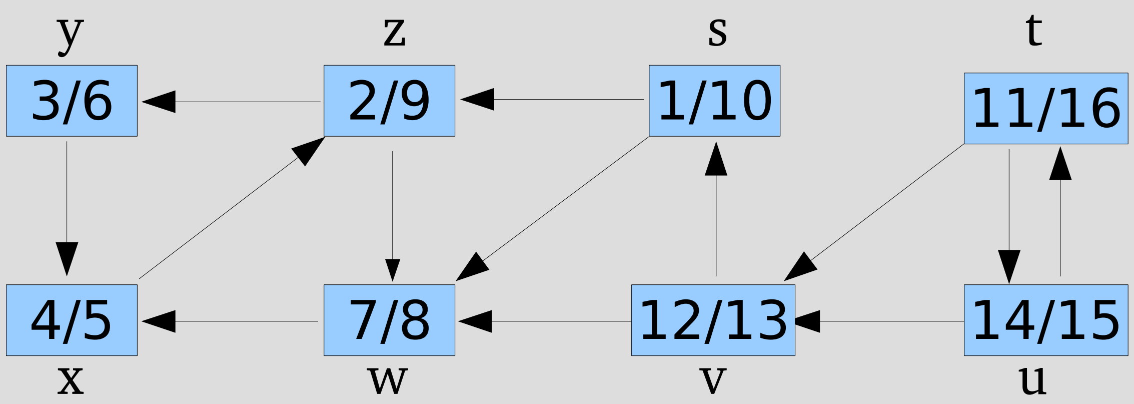
Visit all children recursively (children of children are visited first)

DFS Algorithm/2

- Initialize – color all vertices white
- Visit each and every white vertex using DFS-All (even if there are disconnected trees).
- Each call to DFS(u) roots a new tree of the **depth-first forest** at vertex u
- When DFS returns, each vertex u has assigned
  - a discovery time $d[u]$
  - a finishing time $f[u]$

Example of DFS

- Start with s:



- Explores subgraph s first, t second

DFS Algorithm Running Time

- Running time
  - the loops in DFS-All take time Θ(V) each, excluding the time to execute DFS
  - DFS is called once for every vertex
    - its only invoked on white vertices, and
    - paints the vertex gray immediately
  - for each DFS a loop interates over all *v*.**adj**

$$\sum_{v \in V} |v.adj| = \Theta(E)$$

  - the total cost for DFS is Θ(E)
  - **the running time of DFS-All is Θ(V+E)**

DFS versus BFS

- The BFS algorithms visits all vertices that are reachable from the start vertex. It returns one search tree.
- The DFS-All algorithm visits all vertices in the graph. It may return multiple search trees.
- The difference comes from the applications of BFS and DFS. This behavior of the algo-rithms can easily be changed.

Generic Graph Search

```
GenericGraphSearch(G,s)
for each vertex u ∈ G.V { u.color := white; u.pred := NIL }
s.color := gray
init(GrayVertices)
add(GrayVertices,s)
while not isEmpty(GrayVertices)
  u := extractFrom(GrayVertices)
  for each v ∈ u.adj do
    if v.color = white then
      v.color := gray
      v.pred := u
      addTo(GrayVertices,v)
  u.color := black
```

- BFS if `GrayVertices` is a Queue (FIFO)
- DFS if `GrayVertices` is a Stack (LIFO)

DFS Annotations

- A DFS can be used to annotate vertices and edges with additional information.
  - starttime (when was the vertex visited first)
  - endtime (when was the vertex visited last)
  - edge classification (tree, forward, back or cross edge)
- The annotations reveal useful information about the graph that is used by advanced algorithms.

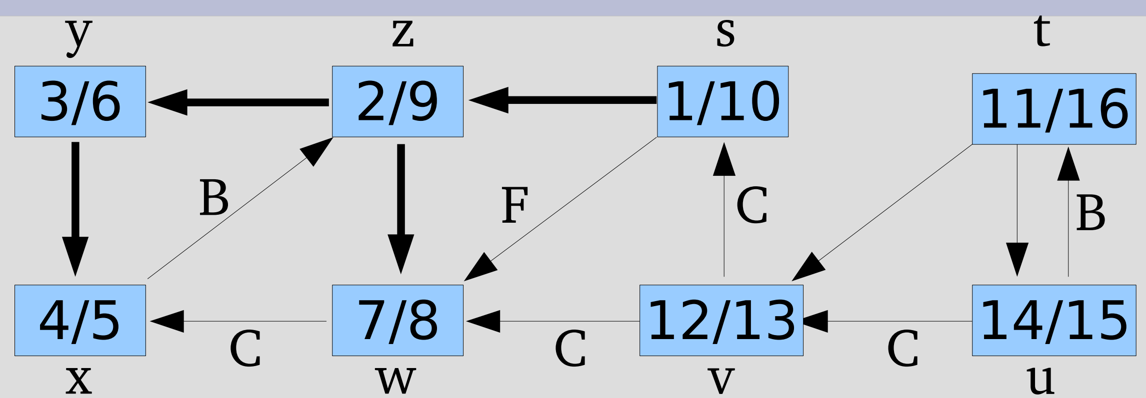
DFS Timestamping

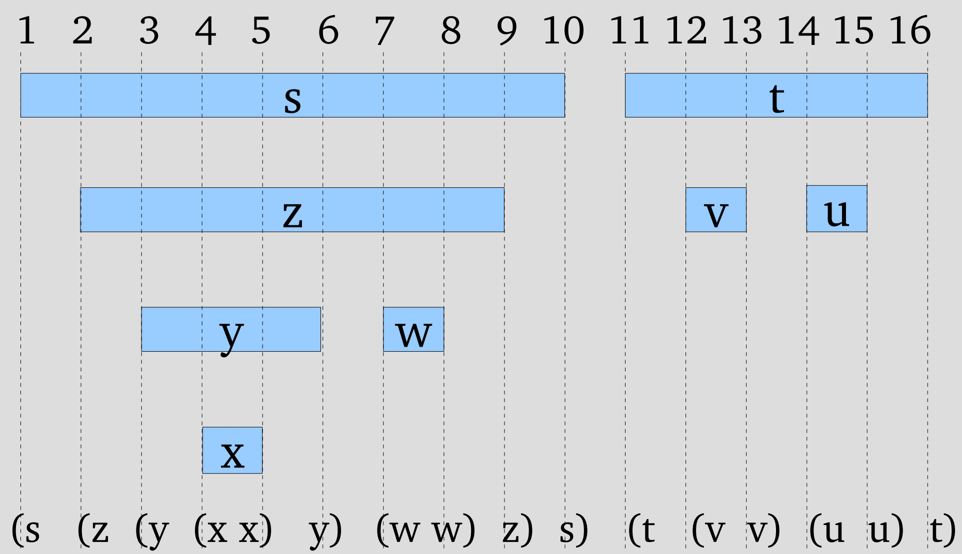
- Vertex *u* is
  - white before *u.starttime*
  - gray between *u.starttime* and *u.endtime*, and
  - black after *u.endtime*
- Notice the structure througout the algorithm
  - gray vertices form a linear chain
  - correponds to a stack of vertices that have not been exhaustively explored (DFS started but not yet finished)

DFS Parenthesis Theorem

- Start and end times have parenthesis structure
  - represent starttime of *u* with left parenthesis "(u"
  - represent endtime of *u* with right parenthesis "u)"
  - history of start- and endtimes makes a well-formed expression (parenthesis are properly nested)
- Intuition for proof: any two intervals are either disjoint or enclosed
  - Overlaping intervals would mean finishing ancestor, before finishing descendant or starting descendant without starting ancestor

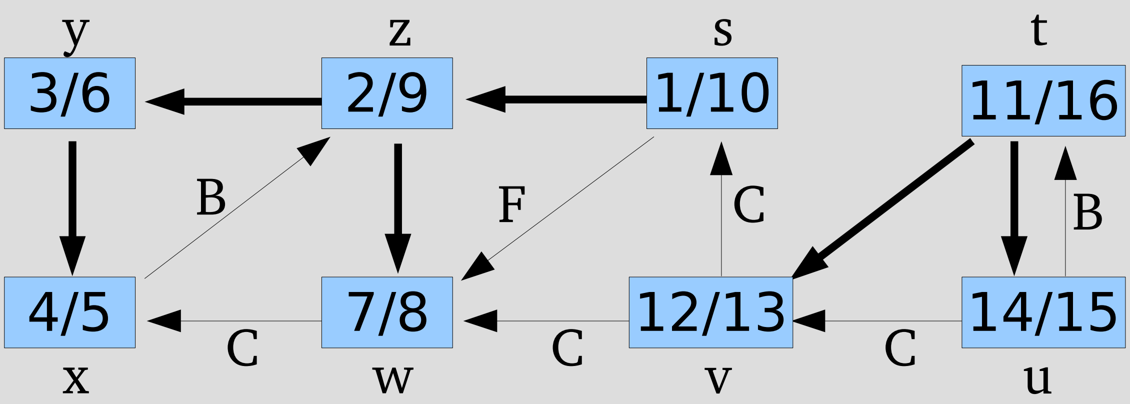
DFS Parenthesis Theorem/2





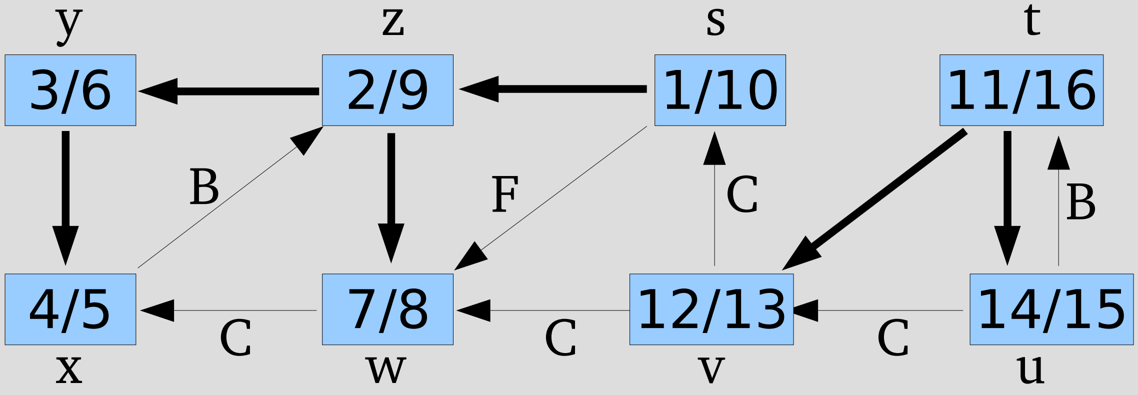
DFS Edge Classification

- Tree edge (gray to white)
  - Edges in depth-first forest
- Back edge (gray to gray)
  - from descendant to ancestor in depth-first tree
  - Self-loops



DFS Edge Classification/2

- Forward edge (gray to black)
  - Nontree edge from ancestor to descendant in depth-first tree
- Cross edge (gray to black)
  - remainder – between trees or subtrees



DFS Edge Classification/3

- In a DFS the color of the next vertex decides the edge type (this makes it impossible to distinguish forward and cross edges).
- Tree and back edges are important.
- Most algorithms do not distinguish between forward and cross edges.

Suggested exercises

- Implement BFS and DFS, both iterative and recursive
- Using paper & pencil, simulate the behaviour of BFS and DFS (and All-DFS) on some graphs, drawing the evolution of the queue/stack

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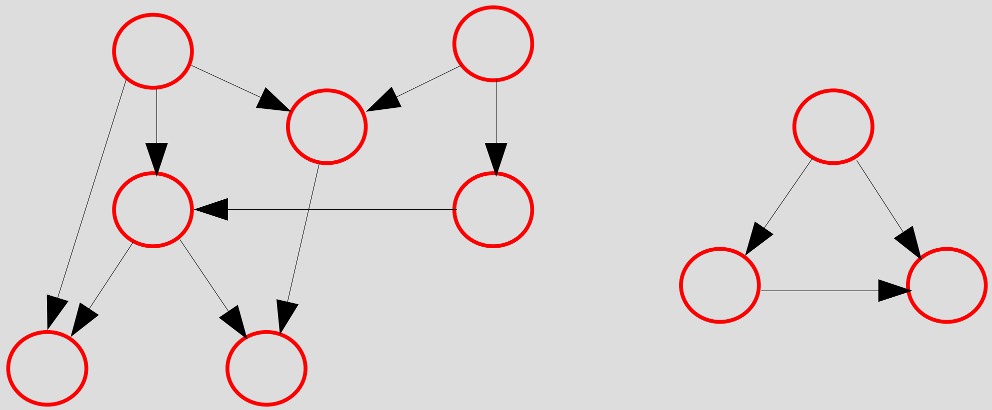
Directed Acyclic Graphs

- A DAG is a directed graph without cycles.



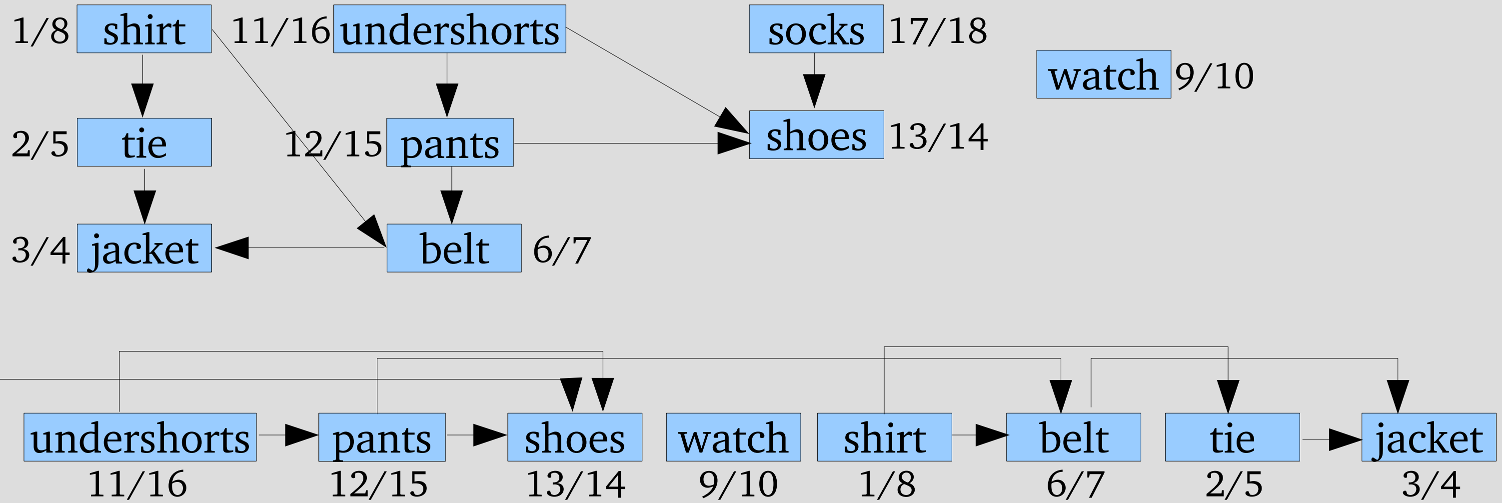
- DAGs are used to indicate precedence among events (event *x* must happen before *y*).
- An example would be a parallel code execution.
- We get total order using **Topological Sorting**.

DAG Theorem

- A directed graph G is acyclic if and only if a DFS of G yields no back edges. Proof:
  - **suppose there is a back edge (u,v);** v is an ancestor of u in DFS forest. Thus, there is a path from v to u in G and (u,v) completes the cycle
  - **suppose there is a cycle c;** let v be the first vertex in c to be discovered and u is the predecessor of v in c.
    - Upon discovering v the whole cycle from v to u is white
    - We visit all nodes reachable on this white path before DFS(v) returns, i.e., vertex u becomes a descendant of v
    - Thus, (u,v) is a back edge
- Thus, we can verify a DAG using DFS.

Topological Sorting Example

- Precedence relations: an edge from *x* to *y* means one must be done with *x* before one can do *y*
- Intuition: can schedule task only when all of its precondition subtasks have been scheduled



Topological Sorting/1

- Sorting of a directed acyclic graph (DAG).
- A topological sort of a DAG is a linear ordering of all its vertices such that for any edge (u,v) in the DAG, u appears before v in the ordering.

Topological Sorting/2

- The following algorithm topologically sorts a DAG.
- The linked lists comprises a total ordering.

```
TopologicalSort(G)
  Call DSF(G) to compute v.endtime for
    each vertex v
  As each vertex is finished, insert it
    at the beginning of a linked list
  Return the linked list of vertices
```

Topological Sorting Correctness

- Claim: DAG $\wedge$ (u,v)$\in$E => u.endtime>v.endtime
- When (u,v) explored, u is gray. We can distinguish three cases:
  - v = gray ==> (u,v) = back edge (cycle, contradiction)
  - v = white ==> v becomes descendant of u
    ==> v will be finished before u
    ==> $v.endtime < u.endtime$
  - v = black ==> v is already finished
    ==> $v.endtime < u.endtime$
- The definition of topological sort is satisfied.

Topological Sorting Running Time

- Running time
  - depth-first search: $O(V+E)$ time
  - insert each of the $|V|$ vertices to the front of the linked list: $O(1)$ per insertion
- Thus the total running time is $O(V+E)$.

Suggested exercises

- Implement topological sorting, with a check for DAG property
- Using paper & pencil, simulate the behaviour of topological sorting

Summary

- Graphs
  - G = (V,E), vertex, edge, (un)directed graph, cycle, connected component, ...
- Graph representation: adjanceny list/matrix
- Basic techniques to traverse/search graphs
  - Breadth-First Search (BFS)
  - Depth-First Search (DFS)
- Topological Sorting

Next Week

- Graphs:
  - Weighted graphs
  - Minimum Spanning Trees
    - Prim’s algorithm
    - Kruskal's algorithm
  - Shortest Paths
    - Dijkstra’s algorithm
    - Bellman-Ford algorithm