Data Structures

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Data structures recap

- Stack (FILO): push, pop, empty – constant time
- Queue (FIFO): insert, delete, empty – constant time
- Heaps: implementation of priority queue
  - Operations: insert ($O(\log n)$), peek (highest priority, $O(1)$), delete (highest priority, $O(\log n)$)
  - Tree representation, with children values smaller (maxheap) or larger (minheap) than the vertex value (weakly sorted)
  - Most efficiently implemented using arrays
  - Efficient sorting (heapsort)

Data structures recap (cont'd)

- Trees: simple connected graph, one vertex may be designated as root
  - For a graph T with n vertices the following statements are equivalent:
    - T is a tree
    - T is connected and acyclic
    - T is connected and has $n-1$ edges
    - T is acyclic and has $n-1$ edges
  - Concepts: parent, ancestor, child, descendant, sibling, leaf, internal note
- Binary tree: each node had at most two children (left and right)
  - In a binary tree of height h with n nodes we have $h \geq \log_2 n$ (or $n \leq 2^h$)
  - Binary tree traversals ($O(n)$ complexity):

```
algorithm PREORDER(T):
    if ¬EMPTY(T) then
        VISIT(T)
        PREORDER(LEFT(T))
        PREORDER(RIGHT(T))

algorithm INORDER(T):
    if ¬EMPTY(T) then
        INORDER(LEFT(T))
        VISIT(T)
        INORDER(RIGHT(T))

algorithm POSTORDER(T):
    if ¬EMPTY(T) then
        POSTORDER(LEFT(T))
        POSTORDER(RIGHT(T))
        VISIT(T)
```

- Binary search tree: the value in every vertex is larger than all the values in its left subtree and smaller than all the values if its right subtree
  - Operations: insert, delete, search ($O(n)$ worst case, $O(\log n)$ if the tree is balanced)
  - Inorder traversal yields sorted sequence

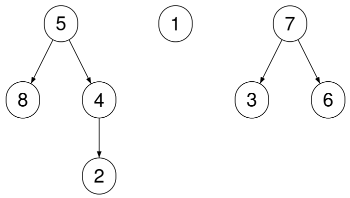
Disjoint sets

- Disjoint sets are non-empty, pairwise disjoint sets
  - Disjoint sets X_i, $1 \leq i \leq n$:
    $\forall 1 \leq i \leq n : X_i \neq \emptyset \quad \wedge \quad \forall 1 \leq i,j \leq n, i \neq j : X_i \cap X_j \neq \emptyset$
  - Each set has a member designated as the representative of that set
- Operations:
  - MAKESET(i): construct a set containing i as its sole element
  - FINDSET(i): return the representative of the set containing i
  - UNION(i, j): replaces the two sets containing i and j with their union; one of the two set representatives becomes the representative of the new set
- Representation: each set can be represented as a tree with the representative in the root
  - The tree does not have to be binary or balanced
- Implementation: disjoint sets over a domain D represented as an array *parent* indexed over D
  - $parent_i$ hold the parent of i in the tree representation, or i if i is the root

Disjoint sets (cont'd)

- Example: $\{2, 4, \underline{5}, 8\}$, $\{\underline{1}\}$, $\{3, 6, \underline{7}\}$

Tree representation:



Array implementation:

$parent =$

1	2	3	4	5	6	7	8
1	4	7	5	5	7	7	5

- A basic implementation:

algorithm MakeSet(i):
  $parent_i \leftarrow i$

algorithm FindSet(i):
  while $parent_i \neq i$ **do** $i \leftarrow parent_i$
  return i

algorithm Union(i, j):
  $x \leftarrow$ FindSet(i)
  $y \leftarrow$ FindSet(j)
  if $x \neq y$ **then** MergeTrees(x,y)

algorithm MergeTrees(i, j):
  $parent_i \leftarrow j$

- The tree representation can become very linear (depending on the sequence of calls to Union), so the running times are as follows:
  - MakeSet: $O(1)$
  - FindSet: $O(n)$
  - Union: $O(n)$ (since it calls FindSet)

Disjoint sets (cont'd)

- Weigthed union: To maintain a smaller tree height for the union we decide what tree gets the root based on the heights of the operands
- Maintain a height for each set (tree)
- During union the tree with the smallest height is attached to the root of the set with the larger height
  - The height stays the same
- When the two operands have the same height attach one to another (no matter which, but consistently)
  - The height increases by one
  - Overall for every two sets joined we have a height increase of at most one so no height in the tree is going over $\log n$
  - Better running times:
    - MakeSet: $O(1)$
    - FindSet: $O(\log n)$
    - Union: $O(\log n)$ (since it calls FindSet)

algorithm WUnion(i, j):
  $x \leftarrow$ FindSet(i)
  $y \leftarrow$ FindSet(j)
  if $x \neq y$ **then** WMergeTrees(x,y)

algorithm WMergeTrees(i, j):
  if $height_i > height_j$ **then** $parent_j \leftarrow i$
  else
    $parent_i \leftarrow j$
    if $height_i = height_j$ **then**
      $height_j \leftarrow height_j + 1$

Disjoint sets (cont'd)

- Collapsing find: Each time we call FindSet we collapse all the nodes we traverse so that they become connected directly to the root

algorithm CFindSet(i):
  if $i \neq parent_i$ **then** $parent_i \leftarrow$ CFindSet($parent_i$)
  return $parent_i$

- When using weighted union alone n MakeSet and m WUnion/FindSet takes $O(n + m \log n)$ time
- When using weighted union and collapsing find n MakeSet and m WUnion/CFindSet takes $O(n + m + \alpha(n, m))$ time where $\alpha(n, m)$ is a constant for all practical purposes

	MakeSet(i)	Find(i)	Union(i, j)	n MakeSet + m Union/Find
Basic impl.	$O(1)$	$O(n)$	$O(n)$	$O(n + nm)$
Weighted union	$O(1)$	$O(\log n)$	$O(\log n)$	$O(n + m \log n)$
Weighted union + collapsing find	$O(1)$	$O(\log n)$	$O(\log n)$	$\approx O(n + m)$

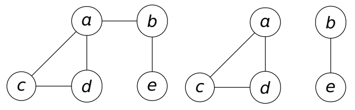
Graphs

- Directed graph (digraph): $G = (V, E)$ where V is a set of vertices and $E \subseteq V \times V$ is the set of edges
  - In a graphical representation edges are shown as arrows between vertices
- Undirected graph: A graph $G = (V, E)$ with the additional property that $(u, v) \in E$ iff $(v, u) \in E$
  - In a graphical representation edges are shown as lines between vertices
- Weighted graph: $G = (V, E, w)$ where (V, E) is a graph and $w : E \rightarrow \mathbb{R}$ associates a weight to each edge
  - In a graphical representation weights are shown as edge labels
- Concepts related to graphs:
  - adjacent vertices, degree, in degree, out degree
  - complement of $G = (V, E)$: $G' = (V, V \times V \setminus E)$
  - path, simple path, cycle, simple cycle
  - acyclic graph
  - length of the shortest path from u to v: Dist(u, v)
  - diameter of $G = (V, E)$: Diam(G) $= \max\{$Dist(u, v) $: u, w \in V\}$
  - subgraph: a subset of edges along with all their vertices
  - induced subgraph: contains all the edges between its vertices
  - Hamiltonian cycle: cycle that contains each vertex exactly once
  - Euler cycle: cycle that contains each edge exactly once

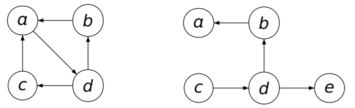
More types of graphs

- (Strongly) connected graph: graph that has a path between each pair of vertices
  - For a connected graph $G = (V, E)$ what is the minimum and the maximum $|E|$ (in terms of $|V|$)?
- Weakly connected graph: directed graph that is not connected but becomes connected if we transform it into an undirected graph
  - No concept of weak connectivity for undirected graphs (they are either connected or not)
- Clique or complete graph: $G = (V, V \times V)$
- Sparse vs dense graphs
- Bipartite graph: $G = (V_1 \uplus V_2, E)$ such that $E \subseteq V_1 \times V_2 \cup V_2 \times V_1$
  - Complete bipartite graph: $G = (V_1 \uplus V_2, V_1 \times V_2 \cup V_2 \times V_1)$

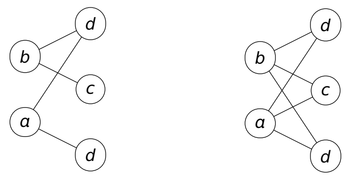
Connected: Unconnected:



Strongly connected: Weakly connected:



Bipartite: Complete bipartite:



Graph representation

- Adjacency matrix
  - For $G = (V, E)$ establish an (arbitrary) order over V, such that we can consider $V = \{0, 1, \ldots, n\}$
  - Then G can be represented as the binary matrix $(G_{ij})_{0 \le i,j \le n}$ such that $G_{ij} = 1$ iff $(i, j) \in E$
  - For a weighted $G = (V, E, w)$ set $G_{ij} = w(i, j)$ if $(i, j) \in E$ and $G_{ij} = \infty$ otherwise

Undirected:

	a	b	c	d	e
a	0	1	1	1	0
b	1	0	0	0	1
c	1	0	0	1	0
d	1	0	1	0	0
e	0	1	0	0	0

Directed:

	a	b	c	d	e
a	0	0	0	1	0
b	1	0	0	0	0
c	1	0	0	1	0
d	0	0	0	0	0
e	0	1	0	0	0

Weighted:

	a	b	c	d	e
a	∞	5	2	1	∞
b	5	∞	∞	∞	8
c	2	∞	∞	2	∞
d	1	∞	2	∞	∞
e	∞	8	∞	∞	∞

- Adjacency list: For each vertex v use a list with exactly all the vertices u such that $(v, u) \in E$
  - Include the weights if it is a weighted graph

a	$\to b \to c \to d$	a	$\to d$	a	$\to b, 5 \to c, 2 \to d, 1$
b	$\to a \to e$	b	$\to a$	b	$\to a, 5 \to e, 8$
c	$\to a \to d$	c	$\to a \to d$	c	$\to a, 2 \to d, 2$
d	$\to a \to c$	d		d	$\to a, 1 \to c, 2$
e	$\to b$	e	$\to b$	e	$\to b, 8$

- Time/space efficiency?

Graph traversal

```
algorithm TRAVERSE(G = (V, E)):
    foreach v ∈ V do
        visit_v ← false
    Let v ∈ V such that visit_v = false
    if v exists then
        LISTTRAVERSE(v)
```

```
algorithm LISTTRAVERSE(v ∈ V):
    open ← ⟨v⟩
    visit_v ← true
    while open ≠ ⟨⟩ do
        u ← HEAD(open)
        Output u
        new ← ⟨x : (u, x) ∈ E ∧ ¬visited_x⟩
        foreach x ∈ new do visit_x ← true
        open ← REST(open) ⊕ new
```

Two different variants of $\oplus$ yield two different traversals:

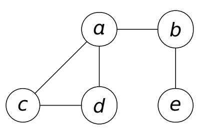
- Breath-first traversal: $L' \oplus L'' = L' + L''$
  - New vertices are added at the end and so *open* implements a queue
- Depth-first traversal: $L' \oplus L'' = L'' + L'$
  - New vertices are added at the beginning and so *open* implements a stack
  - Depth-first traversal can also be implemented recursively:

```
algorithm DFS(G = (V, E)):
    foreach v ∈ V do visit_v ← false
    Let v ∈ V such that visit_v = false
    if v exists then RECDFS(v)
```

```
algorithm RECDFS(v ∈ V):
    Output v
    visit_v ← true
    foreach (v, u) ∈ E ∧ ¬visit_u do
        RECDFS(u)
```

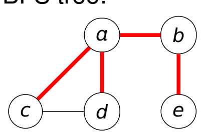

Graph traversal (cont'd)

- Any traversal of a graph G avoids all edges that would result in cycles
- Therefore it only expands (and thus defines) an acyclic subgraph of G = the traversal (DFS or BFS) tree

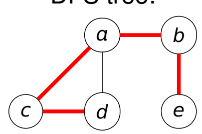


  - Same traversal output starting from a: a, c, d, b, e
  - Different traversal trees:

BFS tree:



DFS tree:



- Both algorithms run in time $O(n + m)$
- Space requirements however are vastly different

Topological sorting on directed graphs

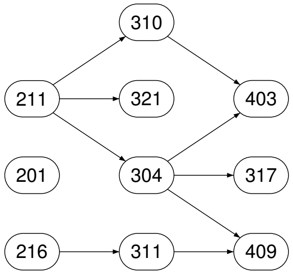
- Given a graph $G = (V, E)$, obtain a linear ordering of V such that for every edge $(u, v) \in E$, u comes before v in the ordering

algorithm TSORT($G = (V, E)$)**:**
  $order \leftarrow \langle\rangle$
  $S \leftarrow V$
  while $S \neq \emptyset$ **do**
    Let $v \in S$ with in-degree 0
    $order \leftarrow order + \langle v\rangle$
    $E \leftarrow E \setminus \{(v, u) \in E\}$
    $V \leftarrow V \setminus v$

algorithm TSORT'($G = (V, E)$)**:**
  $order \leftarrow \langle\rangle$
  $k \leftarrow n$
  foreach $v \in V$ **do** $visit_v \leftarrow$ false
  while $\exists\, v \in V : visit_v =$ false **do**
    RECTOPO(v)

algorithm RECTOPO($v \in V$)**:**
  $visit_v \leftarrow$ true
  foreach $(v, u) \in E \wedge \neg visit_u$ **do**
    RECTOPO(u)
  $order_k \leftarrow v$
  $k \leftarrow k - 1$

- Many practical applications, e.g. sorting over a course prerequisite structure



Possible order:
$\langle 211, 310, 321, 201, 304, 403, 317, 216, 311, 409\rangle$