Advanced algorithms
asymptotic notation,
graphs and their representation in computers

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Introduction

- Subject WWW pages:
  
  https://cw.felk.cvut.cz/doku.php/courses/ae4m33pal/start

- Goals

  Individual implementation of variants of standard (basic and intermediate) problems from several selected IT domains with rich applicability. Algorithmic aspects and effectiveness of practical solutions is emphasized. The seminars are focused mainly on implementation elaboration and preparation, the lectures provide a necessary theoretical foundation.

- Prerequisites

  The course requires **programming skills** in at least one of programming languages C/C++/Java. There are also homework programming tasks. Understanding to basic data structures such as arrays, lists, and files and their usage for data processing is assumed.
Asymptotic upper bound:

$$f(n) \in O(g(n))$$

Meaning:

The value of the function $f$ is on or below the value of the function $g$ (within a constant factor).

Definition:

$$(\exists c > 0)(\exists n_0)(\forall n > n_0) : |f(n)| \leq |c \cdot g(n)|$$
Asymptotic notation

- Asymptotic lower bound:
  \[ f(n) \in \Omega(g(n)) \]

- Meaning:
  The value of the function \( f \) is on or above the value of the function \( g \) (within a constant factor)

- Definition:
  \[
  (\exists c > 0)(\exists n_0)(\forall n > n_0) : |c \cdot g(n)| \leq |f(n)|
  \]
Asymptotic notation

- Asymptotic tight bound:
  \[ f(n) \in \Theta(g(n)) \]

- Meaning:
  The value of the function \( f \) is equal to the value of the function \( g \) (within a constant factor).

- Definition:
  \[
  (\exists c_1, c_2 > 0)(\exists n_0)(\forall n > n_0): |c_1 \cdot g(n)| < |f(n)| < |c_2 \cdot g(n)|
  \]
Example: Consider two-dimensional array $M \times N$ of integers. What is asymptotic growth of searching for the maximum number in this array?

**upper:**
- $O((M+N)^2)$ ✓
- $O(\max(M,N)^2)$ ✓
- $O(N^2)$ ❌
- $O(M \cdot N)$ ✓

**lower:**
- $\Omega(1)$ ✓
- $\Omega(M)$ ✓
- $\Omega(M \cdot N)$ ✓

**tight:**
- $\Theta(M \cdot N)$
A graph is an ordered pair of a set of vertices (nodes) and a set of edges (arcs)

\[ G = (V, E) \]

where \( V \) is a set of vertices and \( E \) is a set of edges such as:

\[ E \subseteq \binom{V}{2} \]

Example:
- \( V=\{a, b, c, d, e\} \)
- \( E=\{\{a, b\}, \{b, e\}, \{e, c\}, \{c, d\}, \{d, a\}, \{a, c\}, \{b, d\}, \{b, c\}\} \)
**Graphs - orientation**

- **Undirected graph**
  - Edge is **not ordered** pair of vertices
  - E={\{a,b\}, \{b,e\}, \{e,c\}, \{c,d\}, \{d,a\}, \{a,c\}, \{b,d\}, \{b,c\}}

- **Directed graph (digraph)**
  - Edge is an **ordered** pair of vertices
  - E={(b,a), (b,e), (c,e), (c,d), (a,d), (c,a), (b,d), (b,c)}
Weighted graph

- A number (weight) is assigned to each edge
- Often, the weight is formalized using a weight function:

$$w : E \rightarrow \mathbb{R}$$

<table>
<thead>
<tr>
<th>Edge</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>{a,b}</td>
<td>1.1</td>
</tr>
<tr>
<td>{b,e}</td>
<td>2.0</td>
</tr>
<tr>
<td>{e,c}</td>
<td>0.3</td>
</tr>
<tr>
<td>{c,d}</td>
<td>6.8</td>
</tr>
<tr>
<td>{d,a}</td>
<td>-2.4</td>
</tr>
<tr>
<td>{a,c}</td>
<td>7.2</td>
</tr>
<tr>
<td>{b,d}</td>
<td>10</td>
</tr>
<tr>
<td>{b,c}</td>
<td>0</td>
</tr>
</tbody>
</table>
Graphs – node degree

- **incidence**
  - If two nodes $x, y$ are linked by edge $e$, nodes $x, y$ are said to be incident to edge $e$ or, edge $e$ is incident to nodes $x, y$.

- **Node degree (for undirected graph)**
  - A function that returns a number of edges incident to a given node.

$$\text{deg}(u) = |\{e \in E | u \in e\}|$$

- $\text{deg}(a)=3$
- $\text{deg}(b)=4$
- $\text{deg}(c)=4$
- $\text{deg}(d)=3$
- $\text{deg}(e)=2$
Node degree (for directed graphs)

- indegree
  \[ \text{deg}^+(u) = |\{ e \in E \mid (\exists v \in V) : e = (v, u) \}| \]

- outdegree
  \[ \text{deg}^-(u) = |\{ e \in E \mid (\exists v \in V) : e = (u, v) \}| \]

\[
\text{deg}^+(a) = 2 \quad \text{deg}^-(a) = 1 \\
\text{deg}^+(b) = 0 \quad \text{deg}^-(b) = 4 \\
\text{deg}^+(c) = 1 \quad \text{deg}^-(c) = 3 \\
\text{deg}^+(d) = 3 \quad \text{deg}^-(d) = 0 \\
\text{deg}^+(e) = 2 \quad \text{deg}^-(e) = 0
\]
**Graphs – handshaking lemma**

- **Handshaking lemma** (for undirected graphs)

\[
\sum_{v \in V} \deg(v) = 2|E|
\]

- Explanation: Each edge is added twice – once for the source node, then once for the target node.

- The variant for directed graphs

\[
\sum_{v \in V} (\deg^+(v) + \deg^-(v)) = 2|E|
\]
complete graph

- Every two nodes are linked by an edge

\[ E = \binom{V}{2} \]

- A consequence

\[ (\forall v \in V) : \deg(v) = |V| - 1 \]
Graphs – path, circuit, cycle

- **path**
  - A **path** is a sequence of vertices and edges \((v_0, e_1, v_1, \ldots, e_t, v_t)\), where all vertices \(v_0, \ldots, v_t\) **differ from each other** and for every \(i = 1, 2, \ldots, t\), \(e_i = \{v_{i-1}, v_i\} \in E(G)\). Edges are traversed in forward direction.

- **circuit**
  - A **circuit** is a closed path, i.e. a sequence \((v_0, e_1, v_1, \ldots, e_t, v_t = v_0)\).

- **cycle**
  - A **cycle** is a closed simple chain. Edges can be traversed in both directions.
connectivity

- Graph G is **connected** if for every pair of vertices $x$ and $y$ in G, there is a path from $x$ to $y$. 

Connected graph

Disconnected graph
tree

The following definitions of a tree (graph G) are equivalent:

- G is a connected graph without cycles.
- G is such a graph so that a cycle occurs if an arbitrary new edges is added.
- G is such a connected graph so that it becomes disconnected if any edge is removed.
- G is a connected graph with \(|V| - 1\) edges.
- G is a graph in which every two vertices are connected by just one path.
Graphs - trees

- Undirected trees
  - A leaf is a node of degree 1.

- Directed trees (the orientation might be opposite sometimes!)
  - A leaf is a node with no outgoing edge.
  - A root is a node with no incoming edge.
Graphs – adjacency matrix

- **Adjacency matrix**
  - Let $G=(V,E)$ be a graph with $n$ vertices.
  - Let’s label vertices $v_1, \ldots, v_n$ (in some order).
  - **Adjacency matrix of graph $G$** is a square matrix

\[
A_G = (a_{i,j})_{i,j=1}^n
\]

defined as follows

\[
a_{i,j} = \begin{cases} 
1 & \text{for } \{v_i, v_j\} \in E \\
0 & \text{otherwise}
\end{cases}
\]
Graphs – adjacency matrix
(for directed graph)

```
 1  2  3  4  5
1 0 1 1 0 0
2 0 0 0 0 0
3 0 1 0 0 0
4 1 1 1 0 0
5 0 1 1 0 0
```

```
v1 --v2 ------v3
    ^  \    
    |    |   
    v    v

v1 ------v4 ------v5
```
Laplacian matrix

Let \( G = (V, E) \) be a graph with \( n \) vertices.

Let’s label vertices \( v_1, \ldots, v_n \) (in an arbitrary order).

**Laplacian matrix of graph \( G \)** is a square matrix defined as follows:

\[
L_G = \left( l_{i,j} \right)_{i,j=1}^{n}
\]

defined as follows:

\[
l_{i,j} = \begin{cases} 
\deg(v_i) & \text{for } i = j \\
-1 & \text{for } \{v_i, v_j\} \in E \\
0 & \text{otherwise}
\end{cases}
\]
Graphs – Laplacian matrix

The Laplacian matrix of a graph is defined as $L = D - A$, where $D$ is the degree matrix (a diagonal matrix with the degree of each vertex on the diagonal) and $A$ is the adjacency matrix of the graph.

For the given graph, the Laplacian matrix is:

$$
L = \begin{pmatrix}
3 & -1 & -1 & -1 & 0 \\
-1 & 4 & -1 & -1 & -1 \\
-1 & -1 & 4 & -1 & -1 \\
-1 & -1 & -1 & 3 & 0 \\
0 & -1 & -1 & 0 & 2 \\
\end{pmatrix}
$$

where $v_1$, $v_2$, $v_3$, $v_4$, and $v_5$ are the vertices of the graph.
Graphs – distance matrix

**Distance matrix**

- Let $G=(V,E)$ is a graph with $n$ vertices and a weight function $w$. Let’s label vertices $v_1, \ldots, v_n$ (in an arbitrary order).

  **Distance matrix of graph $G$** is a square matrix $A_G = (a_{i,j})_{i,j=1}^n$ defined by the formula

  $$a_{i,j} = \begin{cases} w(\{v_i, v_j\}) & \text{for } \{v_i, v_j\} \in E \\ 0 & \text{otherwise} \end{cases}$$
DAG (Directed Acyclic Graph)
- DAG is a directed graph without cycles (=acyclic)
Multigraph (pseudograph)
- It is a graph where multiple edges and/or edges incident to a single node are allowed.
Graphs – incidence matrix

- Incidence matrix

  - Let $G=(V,E)$ be a graph where $|V|=n$ and $|E|=m$.

    Let’s label vertices $v_1, \ldots, v_n$ (in some arbitrary order) and edges $e_1, \ldots, e_m$ (in some arbitrary order). **Incidence matrix of graph G** is a matrix of type

    \[ \{ -1, 0, +1 \}^{n \times m} \]

    defined by the formula

    \[
    (I)_{i,j} = \begin{cases} 
    -1 & \text{for } e_j = (v_i, *) \\
    +1 & \text{for } e_j = (*, v_i) \\
    0 & \text{otherwise}
    \end{cases}
    \]

    In other words, every edge has -1 at the source vertex and +1 at the target vertex. There is +1 at both vertices for undirected graphs.
### Graphs – incidence matrix

**Incidence Matrix**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Graph Representation**

The incidence matrix represents the connections between vertices and edges in a graph. Each row corresponds to a vertex, and each column corresponds to an edge. The entries indicate whether the vertex is incident to the edge (1), not incident (0), or has a specific relationship (e.g., -1 for orientation). The graph visualizes the connections corresponding to the matrix entries.
adjacency list (list of neighbours)

- In an adjacency list representation, we keep, for each vertex in the graph, a list of all other vertices which it has an edge to (that vertex's "adjacency list").
- For instance, the adjacency list of graph G could be an array P of pointers of size $n$, where $P[i]$ points to a linked list of all node indices to which node $v_i$ is linked by an edge (similarly defined for the case of directed graph).

A hash list or a hash table (instead of a linked list) can improve access times to vertices.
### Comparison of graph representations

<table>
<thead>
<tr>
<th></th>
<th>Adjacency Matrix</th>
<th>Laplacian Matrix</th>
<th>Adjacency List</th>
<th>Incidence Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Storage</strong></td>
<td>$</td>
<td>V</td>
<td>\cdot</td>
<td>V</td>
</tr>
<tr>
<td><strong>Add vertex</strong></td>
<td>$O(</td>
<td>V</td>
<td>^2)$</td>
<td>$O(</td>
</tr>
<tr>
<td><strong>Add edge</strong></td>
<td>$O(1)$</td>
<td>$O(</td>
<td>V</td>
<td>)$</td>
</tr>
<tr>
<td><strong>Remove vertex</strong></td>
<td>$O(</td>
<td>V</td>
<td>^2)$</td>
<td>$O(</td>
</tr>
<tr>
<td><strong>Remove edge</strong></td>
<td>$O(1)$</td>
<td>$O(</td>
<td>V</td>
<td>)$</td>
</tr>
<tr>
<td><strong>Check: are u, v adjacent?</strong></td>
<td>$O(1)$</td>
<td>$\deg(v) \in O(</td>
<td>V</td>
<td>)$</td>
</tr>
<tr>
<td><strong>Process vertex neighbours</strong></td>
<td>$O(</td>
<td>V</td>
<td>)$</td>
<td>$\deg(v) \in O(</td>
</tr>
<tr>
<td><strong>Query: get vertex v degree</strong> $\deg(v)$</td>
<td>$O(</td>
<td>V</td>
<td>)$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td><strong>Remarks</strong></td>
<td>Slow to add or remove vertices, because matrix must be resized/copied</td>
<td>When removing edges or vertices, need to find all vertices or edges</td>
<td>Slow to add or remove vertices and edges, because matrix must be resized/copied</td>
<td></td>
</tr>
</tbody>
</table>

**Important**
DFS - Depth First Search

procedure dfs(start_vertex : Vertex)
var to_visit : Stack = empty;
visited : Vertices = empty;
{
    to_visit.push(start_vertex);
    while (size(to_visit) != 0) {
        v = to_visit.pop();
        if v not in visited then {
            visited.add(v);
            for all x in neighbors of v {
                to_visit.push(x);
            }
        }
    }
}
BFS - Breadth First Search

procedure bfs(start_vertex : Vertex)
var to_visit : Queue = empty;
visited : Vertices = empty;
{
    to_visit.push(start_vertex);
    while (size(to_visit) != 0) {
        v = to_visit.pop();
        if v not in visited then {
            visited.add(v);
            for all x in neighbors of v {
                to_visit.push(x);
            }
        }
    }
}
priority queue

- Is a queue with operation **insert to the queue with a priority**.
- In case the priority is the lowest, the queue behaves as push into a normal queue.
- In case the priority is the highest, the queue behaves as push into a stack.
- Both DFS and BFS might be realized using a priority queue with an appropriate value of priority during inserting of elements.
References
