COMP251: Elementary graph algorithms

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Based on (Cormen et al., 2002)
Based on slides from D. Plaisted (UNC)
Graphs

- **Graph G = (V, E)**
  - \( V \) = set of vertices
  - \( E \) = set of edges \( \subseteq (V \times V) \)

- **Types of graphs**
  - Undirected: edge \((u, v) = (v, u)\); for all \( v \), \((v, v) \notin E\) (No self loops.)
  - Directed: \((u, v)\) is edge from \( u \) to \( v \), denoted as \( u \rightarrow v \). Self loops are allowed.
  - Weighted: each edge has an associated weight, given by a weight function \( w : E \rightarrow \mathbb{R} \).
  - Dense: \(|E| \approx |V|^2\).
  - Sparse: \(|E| \ll |V|^2\).

- \(|E| = O(|V|^2)\)
Properties

• If \((u, v) \in E\), then vertex \(v\) is adjacent to vertex \(u\).

• Adjacency relationship is:
  – Symmetric if \(G\) is undirected.
  – Not necessarily so if \(G\) is directed.

• If \(G\) is connected:
  – There is a path between every pair of vertices.
  – \(|E| \geq |V| - 1\).
  – Furthermore, if \(|E| = |V| - 1\), then \(G\) is a tree.
Vocabulary

- Ingoing edges of u: \{ (v,u) \in E \} (e.g. \text{in}(e) = \{ (b,e), (d,e) \})
- Outgoing edges of u: \{ (u,v) \in E \} (e.g. \text{out}(d) = \{ (d,e) \})
- \text{In-degree}(u): | \text{in}(u) |
- \text{Out-degree}(u): | \text{out}(u) |
Representation of Graphs

- Two standard ways.
  - Adjacency Lists.
    - Adjacency Matrix.
Adjacency Lists

• Consists of an array $Adj$ of $|V|$ lists.
• One list per vertex.
• For $u \in V$, $Adj[u]$ consists of all vertices adjacent to $u$.

Note: If weighted, store weights also in adjacency lists.
Storage Requirement

- For directed graphs:
  - Sum of lengths of all adj. lists is
    $$\sum_{v \in V} \text{out-degree}(v) = |E|$$
  - Total storage: $\Theta(V+E)$

- For undirected graphs:
  - Sum of lengths of all adj. lists is
    $$\sum_{v \in V} \text{degree}(v) = 2|E|$$
  - Total storage: $\Theta(V+E)$
Pros and Cons: adj list

• Pros
  – Space-efficient, when a graph is sparse.
  – Can be modified to support many graph variants.

• Cons
  – Determining if an edge \((u,v) \in E\) is not efficient.
    • Have to search in \(u\)’s adjacency list. \(\Theta(\text{degree}(u))\) time.
    • \(\Omega(V)\) in the worst case.
Adjacency Matrix

- \(|V| \times |V|\) matrix \(A\).
- Number vertices from 1 to \(|V|\) in some arbitrary manner.
- \(A\) is then given by:

\[
A[i, j] = a_{ij} = \begin{cases} 
1 & \text{if } (i, j) \in E \\
0 & \text{otherwise}
\end{cases}
\]

\[
A = A^T \text{ for undirected graphs.}
\]
Space and Time

- **Space**: $\Theta(V^2)$.
  - Not memory efficient for large sparse graphs.
- **Time**: to list all vertices adjacent to $u$: $\Theta(V)$.
- **Time**: to determine if $(u, v) \in E$: $\Theta(1)$.
- Can store weights instead of bits for weighted graph.
Graph-searching Algorithms (COMP250)

• Searching a graph:
  – Systematically follow the edges of a graph to visit the vertices of the graph.
• Used to discover the structure of a graph.
• Standard graph-searching algorithms.
  – Breadth-first Search (BFS).
  – Depth-first Search (DFS).
Breadth-first Search

• Expands the frontier between discovered and undiscovered vertices uniformly across the breadth of the frontier.
  – A vertex is “discovered” the first time it is encountered during the search.
  – A vertex is “finished” if all vertices adjacent to it have been discovered.

• Colors the vertices to keep track of progress.
  – White – Undiscovered.
  – Gray – Discovered but not finished.
  – Black – Finished.
    • Colors are required only to reason about the algorithm. Can be implemented without colors.
Breadth-first Search

• **Input:** Graph $G = (V, E)$, either directed or undirected, and *source vertex* $s \in V$.

• **Output:**
  - $d[v] = \text{distance (smallest # of edges, or shortest path) from } s \text{ to } v$, for all $v \in V$. $d[v] = \infty$ if $v$ is not reachable from $s$.
  - $\pi[v] = u$ such that $(u, v)$ is last edge on shortest path $s \sim v$.
    - $u$ is $v$’s predecessor.
  - Builds breadth-first tree with root $s$ that contains all reachable vertices.
Example (BFS)
Example (BFS)

Q: r t x
   1 2 2
Example (BFS)

Q: t x v
   2 2 2
Example (BFS)

Q: x v u
   2 2 3
Example (BFS)

Q: v u y
   2 3 3
Example (BFS)
Example (BFS)

Q: y
3
Example (BFS)

Q: \emptyset
Example (BFS)

BF Tree
Analysis of BFS

• Initialization takes $O(V)$.  
• Traversal Loop
  – After initialization, each vertex is enqueued and dequeued at most once, and each operation takes $O(1)$. So, total time for queuing is $O(V)$.  
  – The adjacency list of each vertex is scanned at most once. The sum of lengths of all adjacency lists is $\Theta(E)$.  
• Summing up over all vertices => total running time of BFS is $O(V+E)$, linear in the size of the adjacency list representation of graph.
Depth-first Search (DFS)

- Explore edges out of the most recently discovered vertex $v$.
- When all edges of $v$ have been explored, backtrack to explore other edges leaving the vertex from which $v$ was discovered (its predecessor).
- “Search as deep as possible first.”
- Continue until all vertices reachable from the original source are discovered.
- If any undiscovered vertices remain, then one of them is chosen as a new source and search is repeated from that source.
Depth-first Search

• **Input:** $G = (V, E)$, directed or undirected. No source vertex given.

• **Output:**
  – 2 timestamps on each vertex. Integers between 1 and $2|V|$.
    • $d[v] = \textit{discovery time}$ ($v$ turns from white to gray)
    • $f[v] = \textit{finishing time}$ ($v$ turns from gray to black)
  – $\pi[v]$ : predecessor of $v = u$, such that $v$ was discovered during the scan of $u$’s adjacency list.

• Uses the same coloring scheme for vertices as BFS.
Pseudo-code

DFS(G)
1. for each vertex $u \in V[G]$
2. do $color[u] \leftarrow$ white
3. $\pi[u] \leftarrow$ NIL
4. $time \leftarrow 0$
5. for each vertex $u \in V[G]$
6. do if $color[u] =$ white
7. then DFS-Visit($u$)

Uses a global timestamp $time$.

DFS-Visit($u$)
1. $color[u] \leftarrow$ GRAY \(\n\) White vertex $u$ has been discovered
2. $time \leftarrow time + 1$
3. $d[u] \leftarrow time$
4. for each $v \in Adj[u]$
5. do if $color[v] =$ WHITE
6. then $\pi[v] \leftarrow u$
7. DFS-Visit($v$)
8. $color[u] \leftarrow$ BLACK \(\n\) Blacken $u$; it is finished.
9. $f[u] \leftarrow time \leftarrow time + 1$
Example (DFS)
Example (DFS)
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Example (DFS)

Starting time \( d(x) \)

Finishing time \( f(x) \)
Example (DFS)
Example (DFS)
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Example (DFS)
Example (DFS)
Analysis of DFS

- Loops on lines 1-2 & 5-7 take $\Theta(V)$ time, excluding time to execute DFS-Visit.
- DFS-Visit is called once for each white vertex $v \in V$ when it’s painted gray the first time. Lines 3-6 of DFS-Visit is executed $|\text{Adj}[v]|$ times. The total cost of executing DFS-Visit is $\sum_{v \in V} |\text{Adj}[v]| = \Theta(E)$
- Total running time of DFS is $\Theta(V+E)$. 
Example (DFS)

- Starting time: \( d(x) \)
- Finishing time: \( f(x) \)
Parenthesis Theorem

**Theorem 1:**
For all \( u, v \), exactly one of the following holds:

1. \( d[u] < f[u] < d[v] < f[v] \) or \( d[v] < f[v] < d[u] < f[u] \) and neither \( u \) nor \( v \) is a descendant of the other.
2. \( d[u] < d[v] < f[v] < f[u] \) and \( v \) is a descendant of \( u \).
3. \( d[v] < d[u] < f[u] < f[v] \) and \( u \) is a descendant of \( v \).

- Like parentheses:
  - OK: ( ) [ ] ( [ ] ) [ ( ) ]
  - Not OK: ( [ ] ) [ ( ] )

**Corollary**

\( v \) is a proper descendant of \( u \) if and only if \( d[u] < d[v] < f[v] < f[u] \).
Example (Parenthesis Theorem)

\[(s \ (z \ (y \ (x \ x) \ y) \ (w \ w) \ z) \ s) \ (t \ (v \ v) \ (u \ u) \ t)\]