CSE 421: Introduction to Algorithms

Trees, BFS

Shayan Oveis Gharan
Claim: If G has no cycle, then it has a vertex of degree $\leq 1$
(So, every tree has a leaf)

Pf: (By contradiction)

Suppose every vertex has degree $\geq 2$.
Start from a vertex $v_1$ and follow a path, $v_1, ..., v_i$ when we are at $v_i$ we choose the next vertex to be different from $v_{i-1}$. We can do so because $\deg(v_i) \geq 2$.

The first time that we see a repeated vertex ($v_j = v_i$) we get a cycle.
We always get a repeated vertex because $G$ has finitely many vertices.
**Claim**: Show that every tree with n vertices has n-1 edges.

**Pf**: By induction.

**Base Case**: n=1, the tree has no edge

**IH**: Suppose every tree with n-1 vertices has n-2 edges

**IS**: Let T be a tree with n vertices.

So, T has a vertex v of degree 1.

Remove v and the neighboring edge, and let T’ be the new graph.

We claim T’ is a tree: It has no cycle, and it must be connected.

So, T’ has n-2 edges and T has n-1 edges.
**Thm:** Any graph $G$ with $n$ vertices having two of the following three properties is a tree and has the third property:

- $G$ has $n-1$ edges
- $G$ is connected
- $G$ has no cycle
Let $G = (V, E)$ be a graph with $n = |V|$ vertices and $m = |E|$ edges.

**Claim:** $0 \leq m \leq \binom{n}{2} = \frac{n(n-1)}{2} = O(n^2)$

**Pf:** Since every edge connects two distinct vertices (i.e., $G$ has no loops) and no two edges connect the same pair of vertices (i.e., $G$ has no multi-edges) it has at most $\binom{n}{2}$ edges.
Sparse Graphs

A graph is called **sparse** if \( m \ll n^2 \) and it is called **dense** otherwise.

Sparse graphs are very common in practice

- Friendships in social network
- Planar graphs
- Web graph

Q: Which is a better running time \( O(n + m) \) vs \( O(n^2) \)?

**A:** \( O(n + m) = O(n^2) \), but \( O(n + m) \) is usually much better.
Storing Graphs (Internally in ALG)

Vertex set $V = \{v_1, ..., v_n\}$.

**Adjacency Matrix: A**

- For all, $i, j, A[i, j] = 1$ iff $(v_i, v_j) \in E$
- Storage: $n^2$ bits

**Advantage:**
- $O(1)$ test for presence or absence of edges

**Disadvantage:**
- Inefficient for sparse graphs both in storage and edge-access
Storing Graphs (Internally in ALG)

Adjacency List:
$O(n+m)$ words

Advantage
- Compact for sparse
- Easily see all edges

Disadvantage
- No $O(1)$ edge test
- More complex data structure
Storing Graphs (Internally in ALG)

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Graph Traversal

Walk (via edges) from a fixed starting vertex \( s \) to all vertices reachable from \( s \).

- Breadth First Search (BFS): Order nodes in successive layers based on distance from \( s \)
- Depth First Search (DFS): More natural approach for exploring a maze; many efficient algs build on it.

Applications:
- Finding Connected components of a graph
- Testing Bipartiteness
- Finding Aritculation points
Breadth First Search (BFS)

Completely **explore** the vertices in order of their distance from \( s \).

Three states of vertices:
\[ \begin{align*}
\bullet & \text{ Undiscovered} \\
\bullet & \text{ Discovered} \\
\bullet & \text{ Fully-explored}
\end{align*} \]

Naturally implemented using a queue
The queue will always have the list of Discovered vertices
BFS implementation

Global initialization: mark all vertices "undiscovered"

BFS(s)

mark s "discovered"
queue = { s }
while queue not empty
    u = remove_first(queue)
    for each edge {u,x}
        if (x is undiscovered)
            mark x discovered
            append x on queue
    mark u fully-explored
BFS(1)
BFS(1)

Queue: 2 3
BFS(1)
BFS(1)

Queue: 4 5 6 7
BFS(1)

Queue: 5 6 7 8 9
BFS(1)

Queue: 7 8 9 10
BFS(1)

Queue:
8 9 10 11
BFS(1)

Queue: 9 10 11 12 13
BFS(1)

Queue:
BFS Analysis

Global initialization: mark all vertices "undiscovered"

BFS(s)

- mark s discovered
- queue = \{ s \}

while queue not empty

- \( u = \text{remove\_first}(\text{queue}) \)
  
  \text{for each edge } \{ u, x \} \text{ if (x is undiscovered)}
  
  - mark x discovered
  - append x on queue

mark u fully-explored

If we use adjacency list: \( O(n) + O(\sum_{v} \text{deg}(v)) = O(m + n) \)
Properties of BFS

- **BFS(s) visits a vertex v** if and only if there is a path from s to v

- Edges into then-undiscovered vertices define a tree – the “Breadth First spanning tree” of G

- Level $i$ in the tree are exactly all vertices v s.t., the shortest path (in G) from the root s to v is of length $i$

- **All nontree edges** join vertices on the same or adjacent levels of the tree
BFS Application: Shortest Paths

BFS Tree gives shortest paths from 1 to all vertices

All edges connect same or adjacent levels
BFS Application: Shortest Paths

BFS Tree gives shortest paths from 1 to all vertices

All edges connect same or adjacent levels
Properties of BFS

Claim: All nontree edges join vertices on the same or adjacent levels of the tree

Pf: Consider an edge \(\{x,y\}\)
Say x is first discovered and it is added to level \(i\).
We show y will be at level \(i\) or \(i + 1\)

This is because when vertices incident to x are considered in the loop, if y is still undiscovered, it will be discovered and added to level \(i + 1\).
Properties of BFS

Lemma: All vertices at level $i$ of BFS(s) have shortest path distance $i$ to $s$.

Claim: If $L(v) = i$ then shortest path $\leq i$

Pf: Because there is a path of length $i$ from $s$ to $v$ in the BFS tree

Claim: If shortest path $= i$ then $L(v) \leq i$

Pf: If shortest path $= i$, then say $s = v_0, v_1, ..., v_i = v$ is the shortest path to $v$.

By previous claim,

$$L(v_1) \leq L(v_0) + 1$$
$$L(v_2) \leq L(v_1) + 1$$

$$L(v_i) \leq L(v_{i-1}) + 1$$

So, $L(v_i) \leq i$.

This proves the lemma.
Why Trees?

Trees are simpler than graphs
  Many statements can be proved on trees by induction

So, computational problems on trees are simpler than general graphs

This is often a good way to approach a graph problem:
• Find a "nice" tree in the graph, i.e., one such that non-tree edges have some simplifying structure
• Solve the problem on the tree
• Use the solution on the tree to find a “good” solution on the graph
Graph Search App: Connected Comp

We want to answer the following type questions (fast):
Given vertices u,v is there a path from u to v in G?

Idea: Create an array A such that
For all u, A[u] is the label of the connected component that contains u

Therefore, question reduces to
If A[u] = A[v]?
Connected Components Implementation

Initial State: All vertices undiscovered, $c \leftarrow 0$
for $v = 1$ to $n$ do
  If state($v$) $\neq$ fully-explored then
    BFS($v$): setting $A[u] \leftarrow c$ for each $u$ found
    (and marking $u$ discovered/fully-explored)
    $c \leftarrow c + 1$

Note: We no longer initialize to undiscovered in the BFS subroutine

Total Cost: $O(m+n)$
  In every connected component with $n_i$ vertices and $m_i$ edges BFS takes time $O(m_i + n_i)$. 
Lesson: We can execute any algorithm on disconnected graphs by running it on each connected component.

We can use the previous algorithm to detect connected components.
There is no overhead, because the algorithm runs in time $O(m+n)$.

So, from now on, we can (almost) always assume the input graph is connected.