

DSC 40B

Theoretical Foundations II

Lecture 12 | Part 1

Warmup: Aggregate Analysis

Time Complexity

```
def full_bfs(graph):
    status = {node: 'undiscovered' for node in graph.nodes}
    for node in graph.nodes:
        if status[node] == 'undiscovered':
            bfs(graph, node, status)

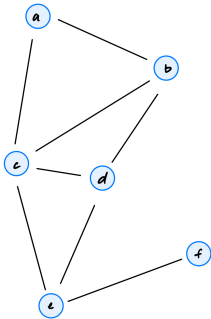
def bfs(graph, source, status=None):
    """Start a BFS at `source`."""
    if status is None:
        status = {node: 'undiscovered' for node in graph.nodes}

    status[source] = 'pending'
    pending = deque([source])

    # while there are still pending nodes
    while pending:
        u = pending.popleft()
        for v in graph.neighbors(u):
            # explore edge (u,v)
            if status[v] == 'undiscovered':
                status[v] = 'pending'
                # append to right
                pending.append(v)
        status[u] = 'visited'
```

Exercise

What is printed if we run a BFS starting at a?



```
...  
while pending:  
    u = pending.popleft()  
    print(f'Popped {u}')    for v in graph.neighbors(u):  
        print(f'Exploring edge ({u}, {v})')        # explore edge (u,v)  
    ...
```

Answer

Popping a

Exploring edge (a, b)

Exploring edge (a, c)

Popping b

Exploring edge (b, a)

Exploring edge (b, c)

Exploring edge (b, d)

Popping c

Exploring edge (c, a)

Exploring edge (c, b)

Exploring edge (c, d)

Exploring edge (c, e)

Popping d

Exploring edge (d, b)

Exploring edge (d, c)

Exploring edge (d, e)

Popping e

Exploring edge (e, c)

Exploring edge (e, d)

Exploring edge (e, f)

Popping f

Exploring edge (f, e)

Aggregate Analysis

- ▶ During any one call to bfs:
 - ▶ Number of printed nodes: ?
 - ▶ Number of printed edges: ?
- ▶ In **aggregate** (over all calls):
 - ▶ Number of printed nodes: *exactly* $|V|$
 - ▶ Number of printed edges: *exactly* $2|E|$

Time Complexity

- ▶ Full BFS takes $\Theta(V + E)$

Time Complexity

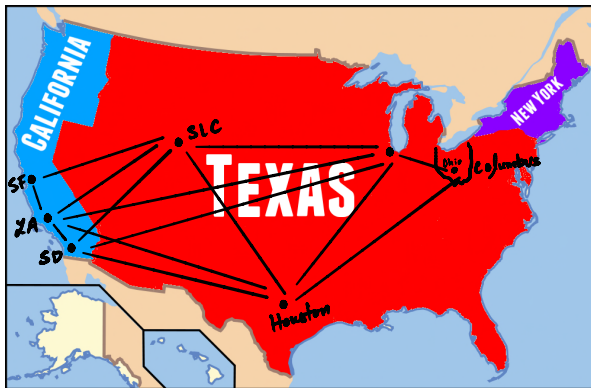
- ▶ Full BFS takes $\Theta(V + E)$
- ▶ Why not just $\Theta(E)$?
- ▶ $\Theta(V + E)$ works *for all graphs*.
 - ▶ If we know more about the number of edges, we might be able to simplify.
 - ▶ E.g., if the graph is **complete**, $E = \Theta(V^2)$, so time complexity is $\Theta(V + V^2) = \Theta(V^2)$.

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Lecture 12 | Part 2

Shortest Paths



Recall

- ▶ The **length** of a path is

$$(\# \text{ of nodes}) - 1$$

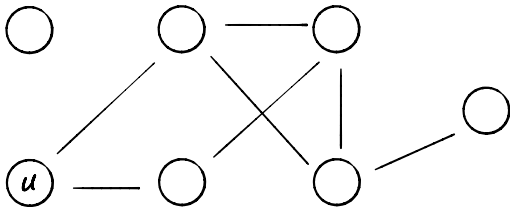
Definitions

- ▶ A **shortest path** between u and v is a path between u and v with smallest possible length.
 - ▶ There may be several, or none at all.
- ▶ The **shortest path distance** is the length of a shortest path.
 - ▶ Convention: ∞ if no path exists.
 - ▶ “the distance between u and v ” means spd .

Today: Shortest Paths

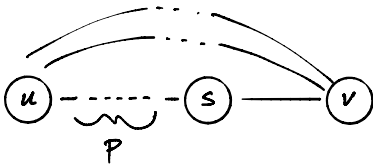
- ▶ **Given:** directed/undirected graph G , source u
- ▶ **Goal:** find shortest path from u to every other node

Example



Key Property

- ▶ A shortest path of length k is composed of:
 - ▶ A **shortest path** of length $k - 1$.
 - ▶ Plus one edge.



Algorithm Idea

- ▶ Find all nodes distance 1 from source.
- ▶ Use these to find all nodes distance 2 from source.
- ▶ Use these to find all nodes distance 3 from source.
- ▶ ...

It turns out...

...this is exactly what BFS does.

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Theoretical Foundations II

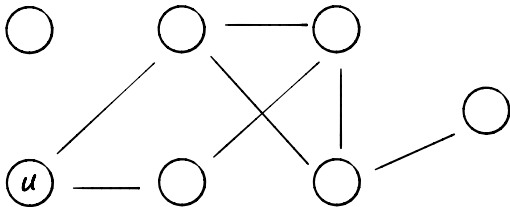
Lecture 12 | Part 3

BFS for Shortest Paths

Key Property of BFS

- ▶ For any $k \geq 1$ you choose:
- ▶ All nodes distance $k - 1$ from source are added to the queue before any node of distance k .
- ▶ Therefore, nodes are “processed” (popped from queue) in order of distance from source.

Example



Discovering Shortest Paths

- ▶ We “discover” shortest paths when we pop a node from queue and look at its neighbors.
- ▶ But the neighbor's status matters!

Consider This

- ▶ We pop a node s .
- ▶ It has a neighbor v whose status is **undiscovered**.
- ▶ We've discovered a **shortest path** to v through s !

Consider This

- ▶ We pop a node s .
- ▶ It has a neighbor v whose status is **pending** or **visited**.
- ▶ We already have a shortest path to v .

Modifying BFS

- ▶ Use BFS “framework”.
- ▶ Return dictionary of **search predecessors**.
 - ▶ If v is discovered while visiting u , we say that u is the **BFS predecessor** of v .
 - ▶ This encodes the shortest paths.
- ▶ Also return dictionary of shortest path distances.

```

def bfs_shortest_paths(graph, source):
    """Start a BFS at `source`."""
    status = {node: 'undiscovered' for node in graph.nodes}
    distance = {node: float('inf') for node in graph.nodes}
    predecessor = {node: None for node in graph.nodes}

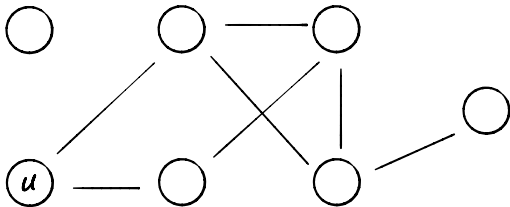
    status[source] = 'pending'
    distance[source] = 0
    pending = deque([source])

    # while there are still pending nodes
    while pending:
        u = pending.popleft()
        for v in graph.neighbors(u):
            # explore edge (u,v)
            if status[v] == 'undiscovered':
                status[v] = 'pending'
                distance[v] = distance[u] + 1
                predecessor[v] = u
                # append to right
                pending.append(v)
        status[u] = 'visited'

    return predecessor, distance

```


Example



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Lecture 12 | Part 4

BFS Trees

Result of BFS

- ▶ Each node reachable from source has a single BFS predecessor.
 - ▶ Except for the source itself.
- ▶ The result is a **tree** (or forest).

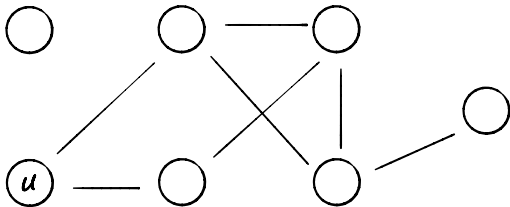
Trees

- ▶ A (free) **tree** is an undirected graph $T = (V, E)$ such that T is connected and $|E| = |V| - 1$.
- ▶ A **forest** is graph in which each connected component is a tree.

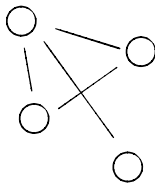
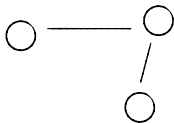
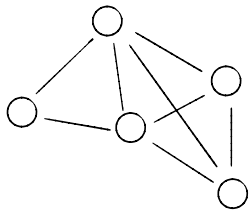
BFS Trees (Forests)

- ▶ If the input is connected, BFS produces a **tree**.
- ▶ If the input is not connected, BFS produces a **forest**.

Example



Example



BFS Trees

- ▶ BFS trees and forests encode shortest path distances.