(Re)Introduction to Graphs and Some Algorithms
Graph Terminology (I)

- A graph is defined by a set of vertices $V$ and a set of edges $E$.
- The edge set must work over the defined vertices in the vertex set.
- Many different types of relationships can be represented as graphs.
- Graphs (specifically edges) can be either directed (eg: driving on a street) or undirected (eg: walking on a street).
- If two vertices are connected by an edge, we say those vertices are adjacent to each other.
- Edges can have values associated with them, in which case we call the graph a weighted graph.
Graph Terminology (II)

• A **path** is a list of edges that are sequentially connected. The **length** of a path is the number of edges. We will say that vertex **b** is **reachable** from **a** if there is a path from **a** to **b**.

• A **cycle** is a path where the starting vertex is also the ending vertex.

• A **Hamiltonian Path** is a path that visits every **vertex** in a graph **exactly once**.

• An **Eulerian Path** is a path that visits every **edge** in a graph **exactly once**.
Graph Representation (Directed)

$V = \{A, B, C, D, E\}$

$E = \{(A,B), (A,D), (B,C), (C,D), (D,A), (E,D), (E,E)\}$
Graph Representation
(Undirected)

\[ V = \{ A, B, C, D, E \} \]
\[ E = \{ (A, B), (A, D), (B, C), (C, D), (D, A), (E, D), (E, E), (B, A), (D, A), (C, B), (D, C), (A, B), (D, E) \} \]
A Proof on Graphs

Definitions: In a directed graph, the in-degree of a vertex is the number of edges going into it and the out-degree of a vertex is the number of edges coming out of it.

Theorem:
\[ \sum_{v \in V} \text{in-degree}(v) = \sum_{v \in V} \text{out-degree}(v) \]

Proof will be by induction. Start with a base case of a graph with a single edge. For the inductive hypothesis, say that for any graph with an edge set of size \(k\) that the theorem holds. Then show that it holds for any graph with an edge set of size \(k+1\).
Inductive Hypothesis

For any graph with edge set of size $k \geq 1$

$$\sum_{v \in V \text{ in-degree}(v)} = \sum_{v \in V \text{ out-degree}(v)}$$

Inductive Step

Show that for any graph $G$ with edge set of size $k+1$ that

$$\sum_{v \in G \text{ in-degree}(v)} = \sum_{v \in G \text{ out-degree}(v)}$$

Let $H$ be a generic particular graph with $k+1$ edges.

Select an edge (call it $e_1$) and remove it from the edge set to create a new graph $H'$.

By our definitions,

$$\sum_{v \in H \text{ in-degree}(v)} = \sum_{v \in H' \text{ in-degree}(v)} + 1$$

$$\sum_{v \in H \text{ out-degree}(v)} = \sum_{v \in H' \text{ out-degree}(v)} + 1$$

Can now ask:

$$\sum_{v \in H' \text{ in-degree}(v)} + 1 = \sum_{v \in H' \text{ out-degree}(v)} + 1$$
Classic Graph Problem

Königsberg Bridge Problem

Seven Bridges. How can you cross all seven without re-using any?
How can we solve Eulerian path?

If all we want is a yes/no answer, it’s fairly easy.

If we also want to find the actual path if it exists, that becomes a much more involved question…

For one point, we need to think about algorithms that are able to traverse graphs. So, let’s look at one…
Breadth-First Search

Given a graph, one way to have an algorithm try to visit every vertex in that graph is via a breadth-first search.

– Select a starting point.
– Visit all vertices that are “one jump” away from it.
– Visit all vertices that are “two jumps” away from it.
– etc.

What if the graph is directed?

If the graph is not connected, what ends up happening?

A simple problem that can be solved using this general technique is that of finding the shortest path between two vertices in an undirected and unweighted graph.
Shortest Path via BFS

Starting at vertex \( s \in V \) generate an array of distances from \( s \) called \( \text{dist[]} \) such that \( \forall v \in V, \text{dist}[v]=\text{length of shortest path from } s \text{ to } v. \)
\[ \text{dist}[s]=0 \]

We will also create a predecessor array of the last vertex we were at before getting to the end of the path from \( s \) to \( v \)
\[ \forall v \in V, \text{pred}[v]=\text{“one step back”} \]
\[ \text{pred}[s]=\text{none} \]

With just these two arrays, we will be able to reconstruct any shortest part request from \( s \) to some vertex.

This is because any sub-path of the optimal path must also be an optimal path between its own endpoints.

If it weren’t, then we could have replaced it and gotten a shorter overall path.
Basic Pseudocode

Start at s.

For each neighbor \( v \) of s

\[
\text{dist}[v] = 1 \\
\text{pred}[v] = s.
\]

Move outwards from each neighbor you’ve seen and set the next “ripple” out as “+1” of the current distance, and set \( \text{pred}[] \) appropriately.

Need a way to make sure we don’t end up in cycles!
Avoiding Cycles

We will assign a color to each vertex based on the following rules:
- white = not seen yet at all
- gray = seen but not processed yet
- black = processed

We will create a queue of gray vertices, and will never add any vertex to the queue more than once.

When we are done processing a vertex (ie: we have touched all its neighbors) we go back to the queue to get the next vertex to process.
More Detailed Pseudocode

BFS (Graph G, vertex s) {
    int size = G.getVertexCount;
    int dist = new int[size];
    vertex pred = new int[size];
    Queue Q= new Queue<vertex>;
    Colors state = new Colors[size];
    for each v in G.V {
        state[v]=white; dist[v]=infinity; pred[v]=none;
    }
    state[s]=gray;  dist[s]=0;  pred[s]=none;
    Q.add(s);
    while (!Q.empty()){
        u=Q.remove();
        for each unvisited v in G.Adj(u) {
            state[v]=gray;
            dist[v]=dist[u]+1;
            pred[v]=u;
            Q.add(v);
        }
        state[u]=black;
    }
}
What’s the runtime?

Each vertex gets enqueued at most one time, so each is processed at most one time.

- Write this up using a summation to represent the processing of all of the vertices...

Our runtime will be order:

|V| for all of the initializations

The while loop’s cost can be seen as the sum across all vertices $u$ in $V$ of:

- the degree($u$) for work inside the for loop
- “+1” for the work outside of the for loop

We can split the summation into two simpler ones and if you work it through, the runtime is $O(|V|+|E|)$. 
What else does BFS give us?

It allows us to organize the entire graph as “ripples” away from a central point.

– This could be useful if we could restate other questions within this framework.

Our predecessor array could be used to create a tree rooted at source $s$ of vertices that can be reached from $s$.

– This is often called a breadth-first tree.

– If we could phrase a problem as a traversal of this tree…
Depth-First Search

You could basically just change the Queue in the BFS code into a Stack.

You could also just write it out as a recursive algorithm.

This approach can also be used to determine what vertices are reachable in $O(|E|+|V|)$ time.
DFS on a Directed Graph with “Timing” Info

We can add more arrays and store information such as when (in terms of a continuously advancing ticker) each vertex is first visited and finally processed.

Even in a connected graph, we might end up having to build a forest of trees to give every vertex a set of times.

– After doing a DFS from a given starting point, if there are vertices with no times, choose one of them, and continue.
Example Graph
Topological Sort of a Digraph

NOTE: This only works if there are no cycles, since if there are cycles there isn’t the notion of a sorted order.

Imagine a graph as beads where the edges are strings of equal length connecting ordered pairs of beads.

You want to arrange the beads so that all edges point left-to-right.

How can you use a DFS with “timing” info to accomplish this?
Strongly Connected Components

We define “strongly connected” to mean that for every pair of vertices \((u,v)\) in the component, there is a path from \(u\) to \(v\) and from \(v\) to \(u\).

In the following graph, what are the strongly connected components?
Finding the SCCs

Step 1: Perform a DFS with “timing” on the graph $G$.

Step 2: Perform a DFS with “timing” on the graph $G^T$ with the added restriction that when you have a choice of vertices, you choose the one with the largest finish time from Step 1’s search.

Every time your algorithm hits a dead-end, you have finished one strongly connected component and are ready to start finding the next one.

Let’s trace this on the graph from the previous slide…
Could you use a BFS or DFS to…

Detect whether a given graph has any cycles?
  – Yes.

Determine whether every vertex is reachable from a particular vertex in a given graph?
  – Yes.

Find the *longest* simple path through a graph between two vertices in an unweighted graph that might contain cycles?
  – No!