Graphs: Structures and Algorithms

- **How do packets of bits/information get routed on the internet**
  - Message divided into packets on client (your) machine
  - Packets sent out using routing tables toward destination
  - Packets may take different routes to destination
  - What happens if packets lost or arrive out-of-order?
- **Routing tables store local information, not global (why?)**

- **What about The Oracle of Bacon, Six Degrees of Separation, Erdos Numbers, and Word Ladders?**
  - All can be modeled using graphs
  - What kind of connectivity does each concept model?

- **Graphs are everywhere in the world of algorithms (world?)**

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Vocabulary

- **Graphs are collections of vertices and edges** (vertex also called node)
  - Edge connects two vertices
    - Direction can be important, directed edge, directed graph
    - Edge may have associated weight/cost
- **A vertex sequence v_0, v_1, ..., v_n-1 is a path** where v_k and v_{k+1} are connected by an edge.
  - If some vertex is repeated, the path is a cycle
  - A graph is connected if there is a path between any pair of vertices

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Vocabulary/Traversals

- **Connected?**
  - Connected components?
    - Weakly connected (directionless)
  - Indegrees? Outdegrees?
- **Starting at 7 where can we get?**
  - **Depth-first** search, envision each vertex as a room, with doors leading out
    - Go into a room, choose a door, mark the door and go out
    - Don’t go into a room you’ve already been in
    - *Backtrack* if all doors marked (to room with unmarked door)
  - Rooms are stacked up, backtracking is really recursion
  - One alternative uses a queue: *breadth-first* search

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Pseudo-code for depth-first search

```cpp
void depthfirst(const string& vertex)
// post: depth-first search from vertex complete
{
    if (! alreadySeen(vertex))
    {
        markAsSeen(vertex);
        cout << vertex << endl;
        for (each v adjacent to vertex)
        {
            depthfirst(v);  
        }  
    }
}
```

- **Clones are stacked up, problem? When are all doors out of vertex opened and visited? Can we make use of stack explicit?**
Other graph questions/operations

- What vertices are reachable from a given vertex
  - Can depth-first search help here?

- What vertex has the highest in-degree (out-degree)?
  - How can we use a map to answer this question?

- Shortest path between any two vertices
  - Breadth first search is storage expensive
  - Dijkstra's algorithm will offer an alternative, uses a priority queue too!

- Longest path in a graph
  - No known efficient algorithm

Breadth first search

- In an unweighted graph this finds the shortest path between a start vertex and every vertex
  - Visit every node one away from start
  - Visit every node two away from start
    - This is every node one away from a node one away
  - Visit every node three away from start

- Like depth first search, but use a queue instead of a stack
  - What features of a queue ensure shortest path?
  - Stack can be simulated with recursion, advantages?
  - How many vertices on the stack/queue?

Pseudocode for breadth first

```cpp
void breadthfirst(const string& vertex)
// post: breadth-first search from vertex complete
{
    tqueue<string> q;
    q.enqueue(vertex);
    distance[vertex] = 0; // start somewhere
    while (q.size() > 0) {
        q.dequeue(current);
        for (each v adjacent to current)
        {
            if (distance[v] == INFINITY) // not seen
                {
                    distance[v] = distance[current] + 1;
                    q.enqueue(v);
                }
        }
    }
}
```

Depth, Breadth, other traversals

- We want to visit every vertex that can be reached from a specific starting vertex
  - Make sure we don’t visit a vertex more than once
    - Why isn’t this an issue in trees?
    - Mark vertex as visited, use set/vector for doing this

- Order in which vertices visited can be important
- Storage and runtime efficiency of traversals important

- What other data structures do we have: stack, queue, ...
  - What happens when we traverse using priority queue?
Graph implementations

- Typical operations on graph:
  - Add vertex
  - Add edge (parameters?)
  - AdjacentVerts(vertex)
  - AllVerts(…)
  - String->int (vice versa)

- Different kinds of graphs
  - Lots of vertices, few edges, sparse graph
    - Use adjacency list
  - Lots of edges (max # ?)
    - dense graph
      - Use adjacency matrix

Graph implementations (continued)

- Adjacency matrix
  - Every possible edge represented, how many?

- Adjacency list uses O(V+E) space
  - What about matrix?
  - Which is better?

- What do we do to get adjacent vertices for given vertex?
  - What is complexity?
  - Compared to adjacency list?

- What about weighted edges?

What about word ladders

- Find a path from white->house changing one letter
  - Real world? Computer vs. human?
    - white write writs waits warts parts ports forte
    - ... rouse house
  - See ladder.cpp program

- How is this a graph problem? What are vertices/edges?
- What about spell-checking, how is it similar?
  - Edge from accomodate to accommodate
  - Can also use tries with wild-cards, e.g., acc*date

What about connected components?

- What computers are reachable from this one? What people are reachable from me via acquaintanceship?
  - Start at some vertex, depth-first search (why not breadth)?
    - Mark nodes visited
  - Repeat, starting from an unvisited vertex (until all visited)

- What is minimal size of a component? Maximal size?
  - What is complexity of algorithm in terms of V and E?

- What algorithms does this lead to in graphs?
Shortest path in weighted graph

- We need to modify approach slightly for weighted graph
  - Edges have weights, breadth first by itself doesn’t work
  - What’s shortest path from A to F in graph below?

- Use same idea as breadth first search
  - Don’t add 1 to current distance, add ???
  - Might adjust distances more than once
  - What vertex do we visit next?

- What vertex is next is key
  - Use greedy algorithm: closest
  - Huffman is greedy, ...

Greedy Algorithms

- A greedy algorithm makes a locally optimal decision that leads to a globally optimal solution
  - Huffman: choose two nodes with minimal weight, combine
    - Leads to optimal coding, optimal Huffman tree
  - Making change with American coins: choose largest coin possible as many times as possible
    - Change for $0.63, change for $0.32
    - What if we’re out of nickels, change for $0.32?

- Greedy doesn’t always work, but it does sometimes
- Weighted shortest path algorithm is Dijkstra’s algorithm, greedy and uses priority queue

Edsger Dijkstra

- Turing Award, 1972
- Operating systems and concurrency
- Algol-60 programming language
- Goto considered harmful
- Shortest path algorithm
- Structured programming
  - “Program testing can show the presence of bugs, but never their absence”
- A Discipline of programming
  - “For the absence of a bibliography I offer neither explanation nor apology”

Dijkstra’s Shortest Path Algorithm

- Similar to breadth first search, but uses a priority queue instead of a queue. Code below is for breadth first search

```java
q.dequeue(vertex w)
foreach (vertex v adjacent to w)
if (distance[v] == INT_MAX)        // not visited
{
    distance[v] = distance[w] + 1
    q.enqueue(v);
}
```

- Dijkstra: Find minimal unvisited node, recalculate costs through node

```java
q.deleteMin(vertex w)
foreach (vertex v adjacent to w)
if (distance[w] + weight(w,v) < distance[v])
{
    distance[v] = distance[w] + weight(w,v)
    q.enqueue(vertex(v, distance[v]));
}
```
Shortest paths, more details

- **Single-source shortest path**
  - Start at some vertex S
  - Find shortest path to every reachable vertex from S
- A set of vertices is processed
  - Initially just S is processed
  - Each pass processes a vertex
  - After each pass, shortest path from S to any vertex using just vertices from processed set (except for last vertex) is always known
- Next processed vertex is closest to S still needing processing

Dijkstra’s algorithm works (greedily)

- Choosing minimal unseen vertex to process leads to shortest paths
  
  q.deleteMin(vertex w)
  
  foreach (vertex v adjacent to w)
  
  if (distance[w] + weight(w,v) < distance[v])
    
    distance[v] = distance[w] + weight(w,v);

    q.enqueue(vertex(v, distance[v]));
  
- We always know shortest path through processed vertices
  - When we choose \( w \), there can’t be a shorter path to \( w \) than \( \text{distance}[w] \) – it would go through processed \( u \), then we would have chosen \( u \) instead of \( w \)

Greedy Algorithms

- Huffman compression is a greedy algorithm that works
  - Where is “greed” used
- Dijkstra’s algorithm is a greedy algorithm that works
  - Which vertex visited?
- Prim’s Minimal-spanning algorithm (see prim.cpp) works
  - How is this algorithm greedy?
- Making change in US is a greedy algorithm that works
  - Minimal coins for change of $0.75, $0.72, ...
  - What if we don’t have nickels: change for $0.32?

Topological sort

- Given a directed acyclic graph (DAG)
  - Order vertices so that any if there is an edge \( (v,w) \), then \( v \) appears before \( w \) in the order
- Prerequisites for a major, take CPS 100 before CPS 130
- Topological sort gives an ordering for taking courses
- Where does ordering start?
  - First vertex has no prereqs
  - “remove” this vertex, continue
  - Depends on in-degree