Graphs, the Internet, and Everything

http://www.caida.org/

Airline routes

Word ladder

Tim Berners-Lee

I want you to realize that, if you can imagine a computer doing something, you can program a computer to do that. Unbounded opportunity... limited only by your imagination. And a couple of laws of physics.

- TCP/IP, HTTP
- How, Why, What, When?
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, 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?)

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 \( v_0, v_1, \ldots, v_{n-1} \) 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

Graph questions/algorithms

- What vertices are reachable from a given vertex?
  - Two standard traversals: depth-first, breadth-first
  - Find connected components, groups of connected vertices

- Shortest path between any two vertices (weighted graphs?)
  - Breadth first search is storage expensive
  - Dijkstra’s algorithm is efficient, uses a priority queue too!

- Longest path in a graph
  - No known efficient algorithm

- Visit all vertices without repeating? Visit all edges?
  - With minimal cost? Hard!

Depth, Breadth, other traversals

- We want to visit every vertex that can be reached from a specific starting vertex (we might try all starting vertices)
  - 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/array/map for this
      - Can keep useful information to help with visited status
  - 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?
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, ...
- Put vertex on queue to start (initially just one)
  - Repeat: take vertex off queue, put all adjacent vertices on
  - Don’t put a vertex on that’s already been visited (why?)
  - When are 1-away vertices enqueued? 2-away? 3-away?
  - How many vertices on queue?

Code for breadth first
```java
public void breadth(String vertex){
    Set<String> visited = new TreeSet<String>();
    Queue<String> q = new LinkedList<String>();
    visited.add(vertex);
    q.add(vertex);
    while (q.size() > 0) {
        String current = q.remove();
        // process current
        for (each v adjacent to current){
            if (!visited.contains(v)){
                // not visited
                visited.add(v);
                q.add(v);
            }
        }
    }
}
```

BFS compared to DFS
```java
public Set<Graph.Vertex> bfs(Graph.Vertex start){
    Set<Graph.Vertex> visited = new TreeSet<Graph.Vertex>();
    Queue<Graph.Vertex> qu = new LinkedList<Graph.Vertex>();
    visited.add(start);
    qu.add(start);
    while (qu.size() > 0){
        Graph.Vertex v = qu.remove();
        for (Graph.Vertex adj : myGraph.getAdjacent(v)){
            if (!visited.contains(adj)){
                visited.add(adj);
                qu.add(adj);
            }
        }
    }
    return visited;
}
```

Pseudo-code for depth-first search
```java
void depthFirst(String vertex){
    if (!alreadySeen(vertex)) {
        markAsSeen(vertex);
        System.out.println(vertex);
        for (each v adjacent to vertex) {
            depthFirst(v);
        }
    }
}
```

- Clones are stacked up, problem? Can we make use of stack explicit?
11.13 BFS becomes DFS

```java
public Set<Graph.Vertex> dfs(Graph.Vertex start) {
    Set<Graph.Vertex> visited = new TreeSet<Graph.Vertex>();
    Queue<Graph.Vertex> qu = new LinkedList<Graph.Vertex>();
    visited.add(start);
    qu.add(start);
    while (qu.size() > 0) {
        Graph.Vertex v = qu.remove();
        for (Graph.Vertex adj : myGraph.getAdjacent(v)) {
            if (!visited.contains(adj)) {
                visited.add(adj);
                qu.add(adj);
            }
        }
    }
    return visited;
}
```

11.14 DFS arrives

```java
public Set<Graph.Vertex> dfs(Graph.Vertex start) {
    Set<Graph.Vertex> visited = new TreeSet<Graph.Vertex>();
    Stack<Graph.Vertex> qu = new Stack<Graph.Vertex>();
    visited.add(start);
    qu.push(start);
    while (qu.size() > 0) {
        Graph.Vertex v = qu.pop();
        for (Graph.Vertex adj : myGraph.getAdjacent(v)) {
            if (!visited.contains(adj)) {
                visited.add(adj);
                qu.push(adj);
            }
        }
    }
    return visited;
}
```

11.15 What is the Internet?

- The Internet was originally designed as an "overlay" network running on top of existing phone and other networks. It is based on a small set of software protocols that direct routers inside the network to forward data from source to destination, while applications run on the Internet to rapidly scale into a critical global service. However, this success now makes it difficult to create and test new ways of protecting it from abuses, or from implementing innovative applications and services.

http://www.intel.com/labs/features/idf09041.htm

11.16 How does the Internet work?

- Differences between the Internet and phone networks
  - Dedicated circuits/routes
  - Distributed, end-to-end

- Where is the intelligence?
  - Not in the network, per se, in the design and the ends
  - End-to-end Arguments in System Design

- Success of email, web, etc., relies on not building intelligence into the network
  - What about overlay networks?
  - What about PlanetLab?
Graph implementations

- Typical operations on graph:
  - Add vertex
  - Add edge (parameters?)
  - getAdjacent(vertex)
  - getVertices(..)
  - String->Vertex (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

Adjacency list

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?

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, ...

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?
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 (distance[]) replaces set

```java
Vertex cur = q.remove();
for(Vertex v : adjacent(cur)){
    if (!visited.contains(v)){ // if distance[v] == INFINITY
        visited.add(v);         // distance[v] = distance[cur]+1
        q.add(v);
    }
}
```

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

```java
Vertex cur = pq.remove();
for(Vertex v : adjacent(cur))
    if (distance[cur] + graph.weight(cur,v) < distance[v]) {
        distance[v] = distance[cur] + graph.weight(cur,v);
        pq.add(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

```java
Vertex cur = pq.remove();
for (Vertex v : adjacent(cur))
    if (distance[cur] + graph.weight(cur, v) < distance[v]){
        distance[v] = distance[cur] + graph.weight(cur, v);
        pq.add(v);
    }
```

- We always know shortest path through processed vertices
  - When we choose w, there can’t be a shorter path to w than distance[w] – it would go through processed u, then we would have chosen u instead of w

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- Greedy doesn’t always work, but it does sometimes
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Shafi Goldwasser

- RCS professor of computer science at MIT
  - Co-inventor of zero-knowledge proof protocols

  How do you convince someone that you know something without revealing “something”

- Consider card readers for dorms
  - Access without tracking

Work on what you like, what feels right, I now of no other way to end up doing creative work