

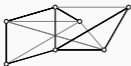
- Recap: arrays, lists, queues, stacks, ...
- Common algorithmic patterns: recursion, brute force, divide and conquer, dynamic programming, greedy algorithms
- Analysis of algorithms: asymptotic, average/worst case analysis, big-O, big-Ω, big-Θ, complexity classes
- Sorting: insertion sort, quicksort, merge sort
- Trees: ordered trees, binary trees, tree traversals, ...
- Priority queues and heaps, heap sort
- Graphs: graph traversal, directed graphs

Spanning trees

reminder

A spanning tree of a graph is

- A **spanning subgraph**: it includes all nodes
- It is a **tree**: it is **acyclic**, and **connected**



Weighted graphs

- A **weighted graph** is a graph, where each edge is associated with a weight
- Weights can be any numeric value, but for some algorithms require
 - Non-negative weights
 - "Euclidean" weights: weights that are proper distance metrics
- Weights often indicate distance or cost, but they can also represent positive relations (e.g., affinity between nodes)
- Weight of a path is the sum of weights of the edges on the path



Minimum spanning trees

- A minimum spanning tree (MST) is a spanning tree of weighted graph with minimum total weight
- MST is a fundamental problem with many applications, including
 - Network design (communication, transportation, electrical, ...)
 - Cluster analysis
 - Approximate solutions to traveling salesman problem
 - Object/network recognition in images
 - Avoiding cycles in broadcasting in communication networks
 - Dithering in images, audio, video
 - Error correction codes
 - DNA sequencing
 - ...



The 'cut property'

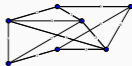
- A **cut** of a graph is a partition that divides its nodes into two disjoint (non-empty) sets
- Given any cut, the edge with the lowest weight across the cut is in the MST



Prim-Jarník algorithm

intuition

- Prim-Jarník algorithm is a greedy algorithm for finding an MST for a weighted undirected graph
- Algorithm starts with a single 'start' node, and grows the MST greedily
- At each step we consider a cut between nodes visited and the rest of the nodes, and select the minimum edge across the cut
- Repeat the process until all nodes are visited



Prim-Jarník algorithm

demonstration

Prim-Jarník algorithm

analysis

- Two loops over number of nodes n , $O(n^2)$ if we need to search
- If we use a priority queue for Q , then complexity becomes $O(m \log m)$

```

1: pick any node s
2: C[s] ← 0
3: for each node v ≠ s do
4:   C[v] ← ∞
5:   E[v] ← None
6: T ← ∅
7: Q ← nodes
8: while Q is not empty do
9:   Find the node v with min C[v]
10:  Connect v to T
11:  for edge (v, w) in Q do
12:    if cost(v, w) < C[w] then
13:      C[w] ← cost(v, w)
14:      E[w] ← v
    
```

Kruskal's algorithm

intuition

- Another popular algorithm for finding MST on undirected graphs
- The main idea is starting with each node in its own partition
- At each iteration, we choose the edge with the minimum weight across any two clusters, and join them
- Algorithm terminates when there are no clusters to join

Kruskal's algorithm

demo



Kruskal's algorithm

analysis

- Loop over edges, but beware of the sorting requirement
- With simple data structures then complexity is $O(m \log m)$

```

1: T ← ∅
2: for each node v do
3:   create_cluster(v)
4: for (u,v) in edges sorted by weight do
5:   if cluster(u) ≠ cluster(v) then
6:     T ← T ∪ {(u,v)}
7:   union(cluster(u), cluster(v))
    
```

Directed trees

- Trees with directed edges come in few flavors
 - A *rooted directed tree* (arborescence) is an acyclic directed graph where all nodes are reachable from the root node through a single directed path (this is what computational linguistics simply calls a *tree*)
 - An *anti-arborescence* is a rooted directed tree where all edges are reversed
 - A *polytree* (also called a *directed tree*) is a directed graph where undirected edges form a tree
- The equivalent of finding an MST in a directed graph is finding a rooted directed tree (arborescence)



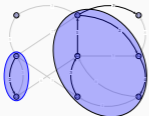
Chu-Liu/Edmonds algorithm

a sketch

- The MST for a directed graph has to start from a designated root node
 - If selected node has any incoming edges, remove them
 - It is also a common practice to introduce an artificial root node with equal-weight edges to all nodes
- For all non-root nodes, select the incoming edge with lowest weight, remove others
- If the resulting graph has no cycles, it is an MST
- If there are cycles break them
 - Consider the cycle as a single node
 - Select the incoming edge that yields the lowest cost if used for breaking the cycle
- Repeat until no cycles remain

Chu-Liu/Edmonds algorithm

demonstration



Chu-Liu/Edmonds algorithm

analysis

- The algorithm is generally defined recursively: at each step, create new graph with a contracted cycle call the procedure with the new graph
- At most n recursions: the cycle has to include more nodes at every step
- At each call, m steps for finding minimum incoming edge (also finding a cycle with $O(n)$, but $m \geq n$)
- The 'vanilla' algorithm runs in $O(mn)$
- There are improved versions

Chu-Liu/Edmonds algorithm in Computational Linguistics

dependency parsing



- In a dependency analysis, the structure of the sentence is represented by asymmetric binary relations between syntactic units
- Each relation defines one of the words as the head and the other as dependent
- Often an artificial root node is used for computational convenience
- The links (relations) may have labels (dependency types)
- A dependency analysis (parse) is simply a rooted directed tree

Chu-Liu/Edmonds for dependency parsing

- Begin with fully connected weighted graph, except the root node has no incoming edges
- Weights are estimated from a treebank, typically determined by a machine learning method trained on a treebank
- We often use probabilities rather than costs/distances, so, rather than minimizing, maximize the weight of the tree
- Given the fully connected graph, now the parsing becomes finding the MST
- This method is one of the most common (and successful) approaches to dependency parsing

Summary

- Minimum spanning trees have many applications
- An MST of a undirected graph can be found (efficiently) using Prim-Jarnik or Kruskal's algorithms
- For directed graph, the corresponding problem can be solved using Chu-Liu/Edmonds algorithm (technically what we find is a rooted directed tree, or arborescence)
- MST also has quite a few applications in CL/NLP

Next:

- Shortest paths

Acknowledgments, credits, references