

- note the chronological order of lecture content:

- Module 1 (Basics and Graphs)
  - Week 1
    - 01 - Minimum Spanning Trees
  - Week 2
    - 02 - Kruskal's Algorithm
    - 03 - Abstract Data Types and Union Find
  - Week 3
    - 04 - Heaps
    - 05 - BFS & DFS
    - 06 - Graph Traversal Applications
  - Week 4
    - 07 - Dijkstra
    - 08 - A\* Search
    - 09 - Bellman-Ford
  - Week 5
    - 10 - Asymptotics
    - 11 - Divide & Conquer: Closest Points
    - 12 - Divide & Conquer: Karatsuba-Strassen
- Module 2 (Trees, Combinatorics, and Dynamic Programming)
  - Week 6
    - 13 - Binary Search Trees
    - 14 - Averaged Analysis
    - 15 - Skip Lists
    - 16 - Splay Trees

- an undirected graph is  $G = (V, E)$ , with  $V$  the vertices,  $E$  the edges.  $V = \{V_1, V_2, \dots, V_n\}$  is a set of objects,  $E$  a set of connections between the objects s.t.  $\forall e \in E, e = \{u, v\}$  with  $u, v \in V$ .

- a directed graph differs in its edges  $E$ , where  $\forall e \in E, e = (u, v)$  with  $u, v \in V$ .

- a subgraph of  $G$  is  $H = (V_H, E_H)$  where  $V_n \subseteq V, E_H \subseteq E$  and  $(\forall e = (u, v) \in E)(u, v \in V_H)$

- connected component: maximal connected subgraph (can't connect more nodes)

- a cycle in  $G = (V, E)$  is a sequence of nodes  $\{v_k\} \in V$  s.t.  $\{v_i, v_{i+1}\} \in E \wedge \{v_1, v_k\} \in E$

- a tree is an acyclic connected graph

- greedy algorithm:

- local optimal decision to try solving a global problem
- decisions are irrevocable (helpful for easy time complexity proofs)

- Minimum spanning tree (MST) problem: given an undirected connected graph  $G$  and nonnegative weights  $d(e) = d(u, v)$ , find the subgraph  $T$  that connects all vertices and minimizes

$$\text{cost}(T) = \sum_{\{u,v\} \in T} d(u,v)$$

- think about why  $T$  must be a tree. if there are cycles, you can trivially rm an edge to cut costs

- to make proofs simpler below, we assume the weights are unique. Then, to prove for cases where weights can be the same, we can just add small unique values. Apparently.

- MST Cycle Property: let a cycle  $C$  be in  $G$ , the heaviest edge on the cycle  $C$  is not in  $G$ 's MST.

- MST Cut Property: let  $S \subseteq V$ , s.t.  $1 \leq |S| < |V|$ , i.e.  $S$  is not empty but not all nodes. Call a pair  $(S, V \setminus S)$  a cut of the graph. Every MST of  $G$  contains the lightest edge on the cut (where an "edge on the cut" is some  $e = \{u, v\}, u \in S, v \in V \setminus S$ ).

- Prim's alg

- tree growing paradigm

- description

- given graph  $G$ , choose arb node  $s$ , the start of  $T$
- repeating  $|V| - 1$  times,
  - add to  $T$ , the lowest edge (and nodes) from "in  $T$ " to "not in  $T$ "

- proof

- The pair ("in  $T$ ", "not in  $T$ ") is a cut of  $G$ . By the Cut Property, the MST contains the lowest cost edge crossing this cut, which is by defin the next edge Prim's adds, i.e. Prim's adds edges in the MST.

- At any point in the algorithm,  $T = (V_T, E_T)$  is a subgraph and a tree.  $T$  grows by 1 vertex and 1 edge at each step, stopping at  $|V_G| - 1$  steps, and so results in a spanning tree. Since these edges are in the MST from above, the spanning tree is the MST.  $\square$

- impl

- (min) heap ADT

- interface
  - `fn new(items) -> Self;`
  - `fn min() -> Item;`
  - `fn insert(item);`
  - `fn delete(item);`
- heap-ordered tree (as an array) implementation

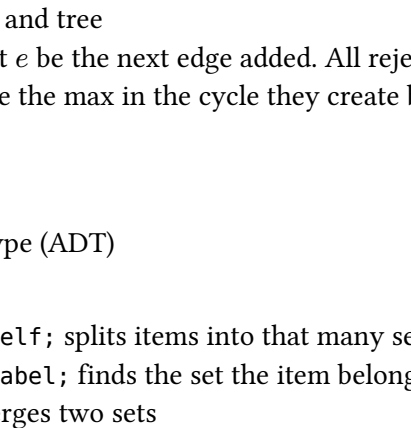


Figure 1: a heaparray. Notice the monotonic decreasing upward. Also notice the array implementation, where  $\text{traverse\_left}(i) = 2i$  and  $\text{traverse\_right}(i) = 2i + 1$ .

- `new`  $\in O(n)$ ; take items as array, for all elements (indices right to left), sift down
- `min`  $\in O(1)$ ; it's at the top of the tree
- `insert`  $\in O(\log n)$ ; insert as leaf preserving shape (aka dense array), sift up
- `delete`  $\in O(\log n)$ ; swap with leaf, delete, sift swapped down

- work of Prim's with a heap is  $O(m \log n)$

1.  $O(n)$ ; create empty heaparray (for max  $n$  items)
2.  $O(1)$ ; choose arb start node  $u$
3.  $O(\log n)$  work per heap operation,  $O(m)$  times total (because we only nbors the edges that much, trust. see your example;  $\forall v \in \text{nbors}(u)$ , if  $v$  is closer to  $T$  than our saved distance from  $v$  to  $T$ , update this distance (and also set parent of  $v$  to  $u$ ). With a heap, `del(v); insert(v, d(u, v))` is related  $\leq$  just decreaseKey( $v$ ,  $d(u, v)$ ).
4.  $O(\log n)$ ; set  $u$  to closest node to  $T$  (min of heap) and delete it
5.  $O(n)$  repetitions; while  $u$  exists, go to (3)

- this is  $O(m \log n + n \log n)$  from (3) and repeating (4), which is  $\in O(m \log n)$

- Reverse Delete

- description

- start with  $G$
- repeating  $|V| - 1$  times
  - remove edges by decreasing weight unless it'd split the graph

- proof

- tree bc we removed all cycles by defin of algorithm
- spanning bc  $|V| - 1$  thing and non-split clause
- minimum: at some step, let  $e$  be the next edge removed. Since it's removed, it's in a cycle and must be the largest edge in it. By cycle property, all removed edges are not in the MST.

- Kruskal's alg

- description

- start with  $T = (V, \{\})$ , i.e. all the nodes and no edges
- repeating  $|V| - 1$  times
  - add edges in increasing order unless it creates a cycle

- proof

- tree bc we didn't connect in a cycle... but why is output connected?
- spanning bc  $|V| - 1$  thing and tree
- minimum: at some step, let  $e$  be the next edge added. All rejected edges would have created cycles, and must be the max in the cycle they create by algo defin. This means, by cycle property, it's MST.

- impl

- union-find abstract data type (ADT)

- interface
  - `fn new(items) -> Self;` splits items into that many sets
  - `fn find(item) -> Label;` finds the set the item belongs to
  - `fn union(a, b);` merges two sets
- array-based implementation

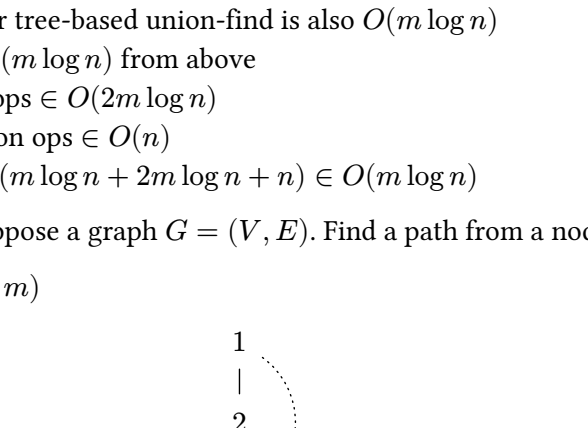


Figure 2: array-based union-find

- `new`  $\in O(n)$ ; creates the three lists
- `find`  $\in O(1)$ ; set array lookup
- `union`  $\in O(\log n)$  amortized;
- procedure
  1. find smaller set ( $x \leq y$ )
  2. for each  $x_i$ , make `set[elem]` be  $y$
  3. update sizes array
  4. prepend smaller to larger list

- proof
  - (2) is computation. others  $O(1)$
  - after  $k$  unions,  $\leq 2k$  items touched
  - for any item  $v$ , `set[v]` is relabeled  $\leq \log_2 2k$  times (TODO WHY) ( $2k$  is the # of items in the largest set????)
  - $2k \log_2 2k \in O(k \log k)$  work
- tree-based implementation

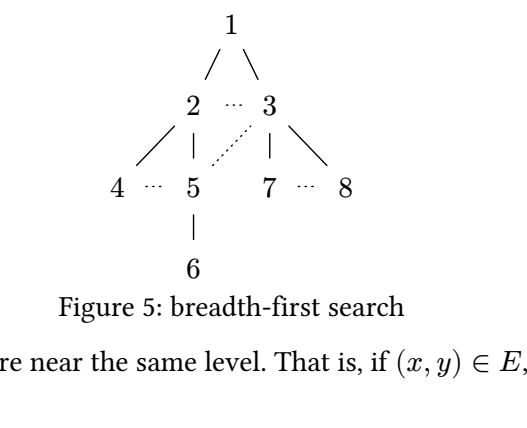


Figure 3: tree-based union-find.

- `new`  $\in O(n)$
- let `struct Node { parent: Option<Node>, height: uint }`
- create an array of node addresses, so we can get from a node id to its node in  $O(1)$
- create all singleton nodes
- `find`  $\in O(\log n)$ ; follow ptrs to the root, which is the set label
- proof
  - set at  $i$  is renamed at most  $\log_2 n$  times because each renaming doubles size
  - depth of tree is number of renamings
  - `union`  $\in O(1)$  (amortized?); move pointer, update height. is this really all we do?

- work of Kruskal's for array-based union-find is  $O(m \log n)$
- sorting edges  $\in O(m \log m) \in O(m \log n)$
- because  $m \leq n^2$ , so  $\log m \leq \log n^2 = 2 \log n$
- at most  $2m$  find operations  $\in O(2m)$  (to check if edge would create cycle)
- at most  $n - 1$  union ops in  $O(n \log n)$
- total runtime  $\in O(m \log n + 2m + n \log n) \in O(m \log n)$

- work of Kruskal's for tree-based union-find is also  $O(m \log n)$
- sorting edges  $\in O(m \log n)$  from above
- at most  $2m$  find ops  $\in O(2m \log n)$
- at most  $n - 1$  union ops  $\in O(n)$
- total runtime  $\in O(m \log n + 2m \log n + n) \in O(m \log n)$

- graph traversal problem: suppose a graph  $G = (V, E)$ . Find a path from a node  $s$  to  $t$  if it exists.

- depth-first search:  $O(n + m)$



Figure 4: depth-first search

- theorem: adjacent edges are not on the same level. That is, if  $(x, y) \in E$ ,  $x$  is either an ancestor or descendant of  $y$ .
- proof: WLOG, let  $x$  ancestor of  $y$ . When we pass  $x$ , we haven't seen  $y$ . All nodes between initially seeing  $x$  and leaving  $x$  are descendants of  $x$ . So,  $y$  must have been explored before leaving  $x$ , as a descendant.

- breadth-first search:  $O(n + m)$

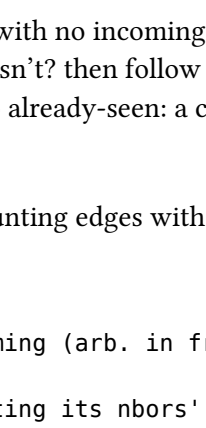


Figure 5: breadth-first search

- theorem: adjacent edges are never the same level. That is, if  $(x, y) \in E$ , then  $|\text{layer}(x) - \text{layer}(y)| \leq 1$
- proof: 1) WLOG, AFSOC that  $\text{layer}(x) < \text{layer}(y) - 1$ . 2) All nbors of  $x$  are added in or before  $\text{layer}(x) + 1$ . By 2,  $\text{layer}(y) \leq \text{layer}(y) + 1$ . But by 1,  $\text{layer}(y) > \text{layer}(x) + 1$ .  $\rightarrow$ contradiction.

- these (and Prim's!) are specific types of tree-growing algorithms

- TreeGrowingAlg(graph G, initial node v, fn findnext)
 

```
T = ({v}, {})  
S = set of nodes adj to v  
while S has items,  
    e = nextEdge(G, S)  
    T = T + e  
    S = updateFrontier(G, S, e)
```

- next/update is pop/push for DFS and de/enqueue for BFS,  $O(m)$  across entire program.
- same logic as Prim's
- everything else in  $O(n)$  (including loop)
- thus, DFS and BFS are  $\in O(n + m)$

- is-bipartite problem

- definition: a graph is bipartite if  $\exists$  a two-coloring, that is, if you can divide the nodes into two colors s.t. all edges connect nodes of diff colors.

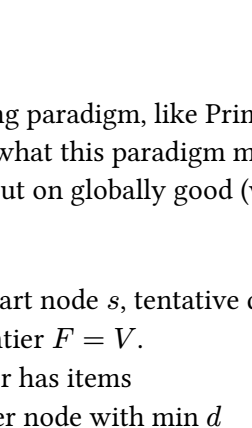


Figure 6: a bipartite graph

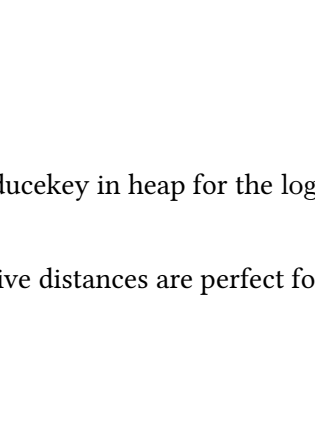


Figure 7: can't have odd cycles

- solution: do a BFS from any node, swapping colors per layer. check if any edge is monolayer (since edges are between adj layers or same layer)
- todo: prove correctness

- topological sort problem: given a DAG, assign an "order" to the nodes (a bijective  $f : V \rightarrow [n]$ ).

- Solution 1

- Theorem: every DAG has a node with no incoming edges
- think about it. what if there wasn't? then follow the edges backward. Since finite nodes in graph, eventually you return to already-seen: a cycle.

- impl/time:

- initialize `num_incoming[w]` by counting edges with DFS in  $O(n + m)$  and a "frontier" of 0-incoming nodes.
- for  $i$  in  $1..n$ :
  - find node  $u$  with no incoming (arb. in frontier)
  - set `f(u) = i`
  - del  $u$  from graph by updating its nbors' `num_incoming` and the frontier

- the loop happens  $n$  times. decrementing the neighbors' `num_incoming` happens  $m$  times overall. total algo time is  $O(n + m)$ .

- proof: todo

- Solution 2

- do a DFS, track entering and leaving order. topological sort is the descending leaving number order.
- this is clearly  $O(n + m)$
- proof: todo

- shortest path problem

| Method       | Time Bound    | Notes   |
|--------------|---------------|---|
| D/BFS        | $O(n + m)$    | unweighted only                                     |
| Dijkstra     | $O(m \log n)$ | pos weights, source to all sinks                    |
| A*           | $O(m \log n)$ | needs an $h$ (pref. admissible), source to one sink |
| Bellman-Ford | $O(nm)$       | can process negative weights                        |

Table 1: summary of options

- as a note, running through these on paper is much better for comprehension than staring at the pseudocode

- Dijkstra

- use tree-growing paradigm, like Prim's
- think about what this paradigm means for neg weights: if I choose a locally good weight, I might miss out on globally good (very negative) weights.

- impl

- define one start node  $S$ , tentative distances  $d$  (all  $\infty$  except  $d[S] = 0$ ), tentative parents  $p$  all None, frontier  $F = S$ .
- while frontier has items
  - $u$  = frontier node with min  $d$
  - remove  $u$  from  $F$  (this "locks  $u$  in": its current  $d$  is the shortest possible.)
  - update  $d$  for neighbors of  $u$  where applicable

- runtime
  - $O(m \log n)$ , like Prim's and co.
  - create frontier as a heap in negligible time
  - every edge processed once, either do nothing or reducekey in heap for the  $\log n$

- proof

- we prove that after considering  $n$  nodes, our tentative distances are perfect for those considered nodes
- notice the base case holds

- by induction,
  - consider the next node to be added with edge  $(u, v)$
  - let  $P_u$  be the path chosen by Dijkstra (smallest to frontier)
  - since the previously considered  $k$  node distances were correct, adding the smallest from the frontier works because we only expose one level of new distance info, which is all we need. We can take the shortest path because the distances are never negative, so later levels can never be better than what we know of this single next level. See diagram in the lecture notes.

- A\*

- impl

- literally just Dijkstra but with  $h[u]$ , a heuristic distance from  $u$  to dest  $t$
- that is, replace "min  $d$ " with "min  $f = d + h$ "
- then, we can stop once we grow the dest  $t$  into our tree

- an admissible  $h$  is one that always underestimates (or is equal to) the real  $u$  to  $t$
- if  $h$  admissible, A\* will find the globally optimal solution (proof omitted)

- Bellman-Ford

- as mentioned above, tree-growing (Dijk/A\*) doesn't work for negative weights. nor do they find (infinitely) negative weight cycles.

- revised problem statement: find that  $\exists$  negative cycle or shortest path

- impl

- again, use  $d[S] = 0, d[\text{else}] = \infty$
- relaxation (Ford) step: find any edge  $(u, v)$  s.t.  $d[v] > d[u] + w(u, v)$ . update  $d$  for that edge.
- relax until can't anymore. if no cycle, this happens at most  $n - 1$  times.
- if we relaxed  $n$  times, there is a cycle (?)

- asymptotics

- we want a formal definition of alg. efficiency for large problems

- big  $O$

- $T(n) \in O(f(n))$  if  $\exists n_0 \geq 0, c \geq 0, T(n) \leq c f(n) \forall n \geq n_0$
- "exists some  $c$  linear multiplier such that  $c f(n)$  dominates  $T(n)$  after some  $n_0$  large number."

- big  $\Omega$

- $T(n) \in \Omega(f(n))$  if  $\exists \varepsilon \geq 0, n_0 \geq 0, T(n) \geq \varepsilon f(n) \forall n \geq n_0$
- "exists some  $\varepsilon$  linear multiplier such that  $\varepsilon f(n)$  is dominated by  $T(n)$ ...

- big  $\Theta$

- $T(n) \in \Theta(f(n))$  if  $T(n) \in O(f(n)) \wedge T(n) \in \Omega(f(n))$

- Theorem:

$$\exists c, \lim_{n \rightarrow \infty} \frac{T(n)}{g(n)} = c \iff T(n) \in \Theta(g(n))$$

- and similarly for the other two big complexities.

- divide and conquer

- time complexity proofs

- set up with old friend recurrence relations

- tree Method

- by induction (used to verify a known/given time bound)

1. show  $T(k) \leq f(k)$  for "small"  $k$
2. assume  $T(k) \leq f(k)$  for  $k < n$
3. show  $T(n) \in O(f(n))$  i.e.  $T(n) \leq f(n)$ , large  $n$ , blah blah blah

- example: with  $T(n) = 2T(\frac{n}{2}) + cn$ , show  $T(k) \leq 2ck \log 2k$  (i.e.  $T(k) \in O(k \log k)$ )
- base case ( $k = 2$ ):  $2c \log 2$  uhhhh what.

- by Master Theorem

- given a recurrence of form

$$T(n) = aT\left(\frac{n}{b}\right) + \Theta(n^a), a \geq 1, b > 1$$

- case 1: if  $i < \log_b a$  (i.e.  $b^i < a$ )  $\rightarrow T(n) = \Theta(n^{b \log_b a})$
- case 2: if  $i = \log_b a$  (i.e.  $b^i = a$ )  $\rightarrow T(n) = \Theta(n^i \log n)$