

Lecture 6

Union-Find

6.1 Overview

In this lecture we describe the *union-find* problem. This is a problem that captures a key task one needs to solve in order to efficiently implement Kruskal's minimum-spanning-tree algorithm. We then give two data structures for it with good amortized running time.

6.2 Motivation

To motivate the union-find problem, let's recall Kruskal's Algorithm for finding a minimum spanning tree (MST) in an undirected graph (see also Appendix B). Remember that an MST is a tree that includes (i.e., spans) all the vertices and out of all such trees has the least total cost.

Kruskal's Algorithm (recap):

- Sort the edges in the given graph G by length and examine them from shortest to longest.
- Put each edge into the current forest if it doesn't form a cycle with the edges chosen so far.

We argue correctness in Appendix B. Today, our concern is running time. The initial step takes time $O(|E| \log |E|)$ to sort. Then, for each edge, we need to test if it connects two different components. If it does, we will insert the edge, merging the two components into one; if it doesn't (the two endpoints are in the same component), then we will skip this edge and go on to the next edge. So, to do this efficiently we need a data structure that can support the basic operations of (a) determining if two nodes are in the same component, and (b) merging two components together. This is the union-find problem.

6.3 The Union-Find Problem

The general setting for the union-find problem is that we are maintaining a collection of disjoint sets $\{S_1, S_2, \dots, S_k\}$ over some universe, with the following operations:

MakeSet(x): create the set $\{x\}$.

Union(x, y): replace the set x is in (let's call it S) and the set y is in (let's call it S') with the single set $S \cup S'$.

Find(x): return the unique ID for the set containing x (this is just some representative element of this set).

Given these operations, we can implement Kruskal's algorithm as follows. The sets S_i will be the sets of vertices in the different trees in our forest. We begin with $\text{MakeSet}(v)$ for all vertices v (every vertex is in its own tree). When we consider some edge (v, w) in the algorithm, we just test whether $\text{Find}(v)$ equals $\text{Find}(w)$. If they are equal, it means that v and w are already in the same tree so we skip over the edge. If they are not equal, we insert the edge into our forest and perform a $\text{Union}(v, w)$ operation. All together we will do $|V|$ MakeSet operations, $|V| - 1$ Unions, and $2|E|$ Find operations.

Notation and Preliminaries: in the discussion below, it will be convenient to define n as the number of MakeSet operations and m as the total number of operations (this matches the number of vertices and edges in the graph up to constant factors, and so is a reasonable use of n and m). Also, it is easiest to think conceptually of these data structures as adding fields to the items themselves, so there is never an issue of "how do I locate a given element v in the structure?".

6.4 Data Structure 1 (list-based)

Our first data structure is a simple one with a very cute analysis. The total cost for the operations will be $O(m + n \log n)$.

In this data structure, the sets will be just represented as linked lists: each element has a pointer to the next element in its list. However, we will augment the list so that each element also has a pointer directly to head of its list. The head of the list is the representative element. We can now implement the operations as follows:

MakeSet(x): just set $x \rightarrow \text{head} = x$. This takes constant time.

Find(x): just return $x \rightarrow \text{head}$. Also takes constant time.

Union(x, y): To perform a union operation we merge the two lists together, and reset the head pointers on one of the lists to point to the head of the other.

Let A be the list containing x and B be the list containing y , with lengths L_A and L_B respectively. Then we can do this in time $O(L_A + L_B)$ by appending B onto the end of A as follows. We first walk down A to the end, and set the final **next** pointer to point to $y \rightarrow \text{head}$. This takes time $O(L_A)$. Next we go to $y \rightarrow \text{head}$ and walk down B , resetting head pointers of elements in B to point to $x \rightarrow \text{head}$. This takes time $O(L_B)$.

Can we reduce this to just $O(L_B)$? Yes. Instead of appending B onto the end of A , we can just splice B into the middle of A , at x . I.e., let $z = x \rightarrow \text{next}$, set $x \rightarrow \text{next} = y \rightarrow \text{head}$, then walk down B as above, and finally set the final **next** pointer of B to z .

Can we reduce this to $O(\min(L_A, L_B))$? Yes. Just store the length of each list in the head. Then compare and insert the shorter list into the middle of the longer one. Then update the length count to $L_A + L_B$.

We now prove this simple data structure has the running time we wanted.

Theorem 6.1 *The above algorithm has total running time $O(m + n \log n)$.*

Proof: The Find and MakeSet operations are constant time so they are covered by the $O(m)$ term. Each Union operation has cost proportional to the length of the list whose head pointers get updated. So, we need to find some way of analyzing the total cost of the Union operations.

Here is the key idea: we can pay for the union operation by charging $O(1)$ to each element whose head pointer is updated. So, all we need to do is sum up the costs charged to all the elements over the entire course of the algorithm. Let's do this by looking from the point of view of some lowly element x . Over time, how many times does x get walked on and have its head pointer updated? The answer is that its head pointer is updated at most $\log n$ times. The reason is that we only update head pointers on the *smaller* of the two lists being joined, so every time x gets updated, the size of the list it is in at least doubles, and this can happen at most $\log n$ times. So, we were able to pay for unions by charging the elements whose head pointers are updated, and no element gets charged more than $O(\log n)$ total, so the total cost for unions is $O(n \log n)$, or $O(m + n \log n)$ for all the operations together. ■

Recall that this is already low-order compared to the $O(m \log m)$ sorting time for Kruskal's algorithm.

6.5 Data Structure 2 (tree-based)

Even though the running time of the list-based data structure was pretty fast, let's think of ways we could make it even faster. One idea is that instead of updating all the head pointers in list B (or whichever was shorter) when we perform a Union, we could do this in a lazy way, just pointing the head of B to the head of A and then waiting until we actually perform a find operation on some item x before updating its pointer. This will decrease the cost of the Union operations but will increase the cost of Find operations because we may have to take multiple hops. Notice that by doing this we no longer need the downward pointers: what we have in general is a collection of trees, with all links pointing *up*. Another idea is that rather than deciding which of the two heads (or roots) should be the new one based on the *size* of their sets, perhaps there is some other quantity that would give us better performance. In particular, it turns out we can do better by setting the new root based on which tree has larger *rank*, which we will define in a minute.

We will prove that by implementing the two optimizations described above (lazy updates and union-by-rank), the total cost is bounded above by $O(m \lg^* n)$, where recall that $\lg^* n$ is the number of times you need to take \log_2 until you get down to 1. For instance,

$$\lg^*(2^{65536}) = 1 + \lg^*(65536) = 2 + \lg^*(16) = 3 + \lg^*(4) = 4 + \lg^*(2) = 5.$$

So, basically, $\lg^* n$ is never bigger than 5. Technically, the running time of this algorithm is even better: $O(m\alpha(m, n))$ where α is the inverse-Ackermann function which grows even more slowly than \lg^* . But the $\lg^* n$ bound is hard enough to prove — let's not go completely overboard!

We now describe the procedure more specifically. Each element (node) will have two fields: a *parent* pointer that points to its parent in its tree (or itself if it is the root) and a rank, which is an integer used to determine which node becomes the new root in a Union operation. The operations are as follows.

MakeSet(x): set x 's rank to 0 and its parent pointer to itself. This takes constant time.

Find(x): starting from x , follow the parent pointers until you reach the root, updating x and all the nodes we pass over to point to the root. This is called *path compression*.

The running time for Find(x) is proportional to (original) distance of x to its root.

Union(x, y): Let $\text{Union}(x, y) = \text{Link}(\text{Find}(x), \text{Find}(y))$, where $\text{Link}(\text{root1}, \text{root2})$ behaves as follows. If the one of the roots has larger rank than the other, then that one becomes the new root, and the other (smaller rank) root has its parent pointer updated to point to it. If the two roots have *equal* rank, then one of them (arbitrarily) is picked to be the new root *and its rank is increased by 1*. This procedure is called *union by rank*.

Properties of ranks: To help us understand this procedure, let's first develop some properties of ranks.

1. The rank of a node is the same as what the height of its subtree would be if we didn't do path compression. This is easy to see: if you take two trees of *different* heights and join them by making the root of the shorter tree into a child of the root of the taller tree, the heights do not change, but if the trees were the *same* height, then the final tree will have its height increase by 1.
2. If x is not a root, then $\text{rank}(x)$ is strictly less than the rank of x 's parent. We can see this by induction: the Union operation maintains this property, and the Find operation only increases the difference between the ranks of nodes and their parents.
3. The rank of a node x can only change if x is a root. Furthermore, once a node becomes a non-root, it is never a root again. These are immediate from the algorithm.
4. There are at most $n/2^r$ nodes of rank $\geq r$. The reason is that when a (root) node first reaches rank r , its tree must have at least 2^r nodes (this is easy to see by induction). Furthermore, by property 2, all the nodes in its tree (except for itself) have rank $< r$, and their ranks are never going to change by property 3. This means that (a) for each node x of rank $\geq r$, we can identify a set S_x of at least $2^r - 1$ nodes of smaller rank, and (b) for any two nodes x and y of rank $\geq r$, the sets S_x and S_y are disjoint. Since there are n nodes total, this implies there can be at most $n/2^r$ nodes of rank $\geq r$.

We're now ready to prove the following theorem.

Theorem 6.2 *The above tree-based algorithm has total running time $O(m \lg^* n)$.*

Proof: Let's begin with the easy parts. First of all, the Union does two Find operations plus a constant amount of extra work. So, we only need to worry about the time for the (at most $2m$) Find operations. Second, we can count the cost of a Find operation by charging \$1 for each parent pointer examined. So, when we do a Find(x), if x was a root then pay \$1 (just a constant, so that's ok). If x was a child of a root we pay \$2 (also just a constant, so that's ok also). If x was lower, then the *very rough* idea is that (except for the last \$2) every dollar we spend is shrinking the tree because of our path compression, so we'll be able to amortize this cost somehow. For the remaining part of the proof, we're only going to worry about the steps taken in a Find(x) operation up until we reach the child of the root, since the remainder is just constant time per operation. We'll analyze this using the ranks, and the properties we figured out above.

Step 1: let's imagine putting non-root nodes into buckets according to their rank. Bucket 0 contains all non-root nodes of rank 0, bucket 1 has all of rank 1, bucket 2 has ranks 2 through $2^2 - 1$, bucket 3 has ranks 2^2 through $2^{2^2} - 1$, bucket 4 has ranks 2^{2^2} through $2^{2^{2^2}} - 1$, etc. In general, a bucket has ranks r through $2^r - 1$. In total, we have $O(\lg^* n)$ buckets.

The point of this definition is that the number of nodes with rank in any given bucket is at most $n/(\text{upper bound of bucket} + 1)$, by property (4) of ranks above.

Step 2: When we walk up the tree in the $\text{Find}(x)$ operation, we need to charge our steps to something. Here's the rule we will use: if the step we take moves us from a node u to a node v such that v is in the *same* bucket as u , then we charge it to node u (the walk-ee). But if v is in a higher bucket, we charge that step to x (the walk-er).

The easy part of this is the charge to x . We can move up in buckets at most $O(\lg^* n)$ times, since there are only $O(\lg^* n)$ different buckets. So, the total cost charged to the walk-ers (adding up over the m Find operations) is at most $O(m \lg^* n)$.

The harder part is the charge to the walk-ee. The point here is that first of all, the node u charged is not a root, so its rank is never going to change. Secondly, every time we charge this node u , the rank of its new parent (after path compression) is at least 1 larger than the rank of its previous parent by property 2. Now, it is true that increasing the rank of u 's parent could conceivably happen $\log n$ times, which to us is a "big" number. *But*, once its parent's rank becomes large enough that it is in the next bucket, we never charge node u again as walk-ee. So, the bottom line is that the maximum charge any node u gets is the range of his bucket.

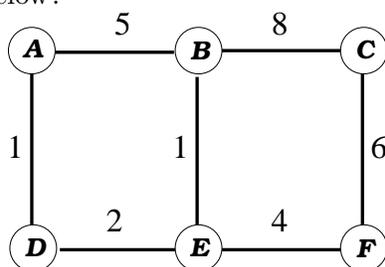
To finish the proof, we just said that a bucket of upper bound $B - 1$ has at most n/B elements in it, and its range is $\leq B$. So, the total charge to all walk-ees in this bucket over the entire course of the algorithm is at most $(n/B)B = n$. (Remember that the only elements being charged are non-roots, so once they start getting charged, their rank is fixed so they can't jump to some other bucket and start getting charged there too.) This means the *total* charge of this kind summed *over all buckets* is at most n times the number of buckets which is $O(n \lg^* n)$. ■ (Whew!)

Appendix B

Minimum Spanning Trees

A **spanning tree** of a graph is a tree that touches all the vertices (so, it only makes sense in a connected graph). A **minimum spanning tree** (MST) is a spanning tree whose sum of edge lengths is as short as possible (there may be more than one). We will sometimes call the sum of edge lengths in a tree the *size* of the tree. For instance, imagine you are setting up a communication network among a set of sites and you want to use the least amount of wire possible. *Note:* our definition is only for *undirected* graphs.

What is the MST in the graph below?



B.1 Prim's algorithm

Prim's algorithm is an MST algorithm that works much like Dijkstra's algorithm does for shortest path trees, if you are familiar with that. In fact, it's even simpler (though the correctness proof is a bit trickier).

Prim's Algorithm:

1. Pick some arbitrary start node s . Initialize tree $T = \{s\}$.
2. Repeatedly add the shortest edge incident to T (the shortest edge having one vertex in T and one vertex not in T) until the tree spans all the nodes.

For instance, what does Prim's algorithm do on the above graph?

Before proving correctness for the algorithm, we first need a useful fact about spanning trees: if you take any spanning tree and add a new edge to it, this creates a cycle. The reason is that there

already was one path between the endpoints (since it's a *spanning tree*), and now there are two. If you then remove any edge in the cycle, you get back a spanning tree (removing one edge from a cycle cannot disconnect a graph).

Theorem B.1 *Prim's algorithm correctly finds a minimum spanning tree of the given graph.*

Proof: We will prove correctness by induction. Let G be the given graph. Our inductive hypothesis will be that the tree T constructed so far is consistent with (is a subtree of) some minimum spanning tree M of G . This is certainly true at the start. Now, let e be the edge chosen by the algorithm. We need to argue that the new tree, $T \cup \{e\}$ is also consistent with some minimum spanning tree M' of G . If $e \in M$ then we are done ($M' = M$). Else, we argue as follows.

Consider adding e to M . As noted above, this creates a cycle. Since e has one endpoint in T and one outside T , if we trace around this cycle we must eventually get to an edge e' that goes back in to T . We know $len(e') \geq len(e)$ by definition of the algorithm. So, if we add e to M and remove e' , we get a new tree M' that is no larger than M was and contains $T \cup \{e\}$, maintaining our induction and proving the theorem. ■

Running time: To implement this efficiently, we can store the neighbors of the current tree in a priority-queue (pqueue), with priority-value equal to the length of the shortest edge between that node and the current tree. We add a new node into the tree using a remove-min operation (taking the node of smallest priority-value out of the pqqueue); then, after adding this node, we examine all outgoing edges and for each one that points to a node not in the tree we either (a) add it into the pqqueue if it is not there already, or (b) perform a “decrease-key” operation if it was in there already but the new edge is shorter. This will give us $O(m \log n)$ running time if we implement the pqqueue using a standard heap, or $O(m + n \log n)$ running time if we use something called a Fibonacci heap.

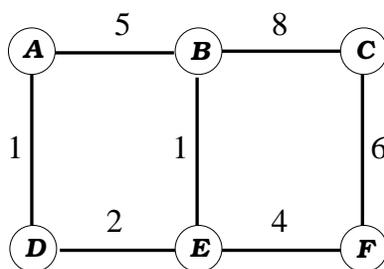
B.2 Kruskal's algorithm

Here is another algorithm for finding minimum spanning trees called Kruskal's algorithm. It is also greedy but works in a different way.

Kruskal's Algorithm:

Sort edges by length and examine them from shortest to longest. Put each edge into the current forest (a forest is just a set of trees) if it doesn't form a cycle with the edges chosen so far.

E.g., let's look at how it behaves in the graph below:



Kruskal's algorithm sorts the edges and then puts them in one at a time so long as they don't form a cycle. So, first the AD and BE edges will be added, then the DE edge, and then the EF edge. The AB edge will be skipped over because it forms a cycle, and finally the CF edge will be added (at that point you can either notice that you have included $n - 1$ edges and therefore are done, or else keep going, skipping over all the remaining edges one at a time).

Theorem B.2 *Kruskal's algorithm correctly finds a minimum spanning tree of the given graph.*

Proof: We can use a similar argument to the one we used for Prim's algorithm. Let G be the given graph, and let F be the forest we have constructed so far (initially, F consists of n trees of 1 node each, and at each step two trees get merged until finally F is just a single tree at the end). Assume by induction that there exists an MST M of G that is consistent with F , i.e., all edges in F are also in M ; this is clearly true at the start when F has no edges. Let e be the next edge added by the algorithm. Our goal is to show that there exists an MST M' of G consistent with $F \cup \{e\}$.

If $e \in M$ then we are done ($M' = M$). Else add e into M , creating a cycle. Since the two endpoints of e were in different trees of F , if you follow around the cycle you must eventually traverse some edge $e' \neq e$ whose endpoints are also in two different trees of F (because you eventually have to get back to the node you started from). Now, both e and e' were eligible to be added into F , which by definition of our algorithm means that $\text{len}(e) \leq \text{len}(e')$. So, adding e and removing e' from M creates a tree M' that is also a MST and contains $F \cup \{e\}$, as desired. ■

Running time: The first step is sorting the edges by length which takes time $O(m \log m)$. Then, for each edge we need to test if it connects two different components. This seems like it should be a real pain: how can we tell if an edge has both endpoints in the same component? It turns out there's a nice data structure called the *Union-Find* data structure for doing this operation. It is so efficient that it actually will be a low-order cost compared to the sorting step.