CSE 373: Data Structures and Algorithms

Lecture 24: Disjoint Sets
Kruskal's Algorithm Implementation

Kruskals():
   sort edges in increasing order of length \((e_1, e_2, e_3, ..., e_m)\).

   \(T := \{\}\).  

   for \(i = 1\) to \(m\) 
       if \(e_i\) does not add a cycle: 
           add \(e_i\) to \(T\).

   return \(T\).

• But how can we determine that adding \(e_i\) to \(T\) won't add a cycle?
Disjoint-set Data Structure

• Keeps track of a set of elements partitioned into a number disjoint subsets
  – two sets are said to be disjoint if they have no elements in common

• Initially, each element $e$ is a set in itself:
  – e.g., $\{ \{e_1\}, \{e_2\}, \{e_3\}, \{e_4\}, \{e_5\}, \{e_6\}, \{e_7\} \}$
Operations: Union

• Union(x, y) – Combine or merge two sets x and y into a single set
  – Before:
    \{\{e_3, e_5, e_7\}, \{e_4, e_2, e_8\}, \{e_9\}, \{e_1, e_6\}\}

  – After Union(e_5, e_1):
    \{\{e_3, e_5, e_7, e_1, e_6\}, \{e_4, e_2, e_8\}, \{e_9\}\}
Operations: Find

• Determine which set a particular element is in
  – Useful for determining if two elements are in the same set

• Each set has a unique name
  – name is arbitrary; what matters is that find(a) == find(b) is true only if a and b in the same set
  – one of the members of the set is the "representative" (i.e. name) of the set
  – \{e_3, e_5, e_7, e_1, e_6\}, \{e_4, e_2, e_8\}, \{e_9\}
Operations: Find

• **Find(x)** – return the name of the set containing x.
  
  – {{e$_3$, e$_5$, e$_7$, e$_1$, e$_6$}, {e$_4$, e$_2$, e$_8$}, {e$_9$}}
  
  – Find(e$_1$) = e$_5$
  
  – Find(e$_4$) = e$_8$
Kruskal's Algorithm Implementation (Revisited)

Kruskals():

  sort edges in increasing order of length \( (e_1, e_2, e_3, ..., e_m) \).

  initialize disjoint sets.

  \( T := \{ \}. \)

  for \( i = 1 \) to \( m \)
    \( \text{let } e_i = (u, v). \)
    \( \text{if } \text{find}(u) \neq \text{find}(v) \)
      \( \text{union}(\text{find}(u), \text{find}(v)). \)
      \( \text{add } e_i \text{ to } T. \)

return \( T. \)

• What does the disjoint set initialize to?
• How many times do we do a union?
• How many time do we do a find?
• What is the total running time if we have \( n \) nodes and \( m \) edges?
Disjoint Sets with Linked Lists

• Approach 1: Create a linked list for each set.
  – last/first element is representative
  – cost of union? find?

• Approach 2: Create linked list for each set. Every element has a reference to its representative.
  – last/first element is representative
  – cost of union? find?
Disjoint Sets with Trees

- Observation: *trees* let us find many elements given one root (i.e. representative)...

- Idea: if we *reverse* the pointers (make them point up from child to parent), we can find a single root from many elements...

- Idea: Use one tree for each subset. The name of the class is the tree root.
Up-Tree for Disjoint Sets

Initial state

1  2  3  4  5  6  7

Intermediate state

1  3

2

5  7

4

6

Roots are the names of each set.
Union Operation

• Union(x, y) – assuming x and y roots, point x to y.
Find Operation

• Find(x): follow x to root and return root

Find(6) = 7
Simple Implementation

• Array of indices

<table>
<thead>
<tr>
<th>up</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>7</th>
<th>7</th>
<th>5</th>
<th>0</th>
</tr>
</thead>
</table>

Up[x] = 0 means x is a root.
Union

Union(up[] : integer array, x,y : integer) : {
    //precondition: x and y are roots/
    up[x] := y
}

Constant Time!
Find

Find(up[] : integer array, x : integer) : integer {
    //precondition: x is in the range 1 to size
    if up[x] == 0
        return x
    else
        return Find(up, up[x])
}

• Exercise: write an iterative version of Find.
A Bad Case

1 2 3 \ldots n

Union(1,2)

Union(2,3)

\vdots

Union(n-1, n)

Find(1) \ n \text{ steps}!!
Improving Find

Can we do better?  Yes!

1. Improve union so that \textit{find} only takes \(\Theta(\log n)\)
   • Union-by-size
   • Reduces complexity to \(\Theta(m \log n + n)\)

2. Improve find so that it becomes even better!
   • Path compression
   • Reduces complexity to almost \(\Theta(m + n)\)
Union by Rank

• Union by Rank (also called Union by Size)
  – Always point the smaller tree to the root of the larger tree

![Diagram of union by rank with nodes and arrows indicating the tree structure, including an example union operation Union(1,7).]
Example Again

1 2 3 \ldots n

Union(1,2)

Union(2,3)

\vdots

Union(n-1,n)

Find(1) constant time
Improved Runtime for Find via Union by Rank

- Depth of tree affects running time of Find
- Union by rank only increases tree depth if depth were equal
- Results in $O(\log n)$ for Find
Elegant Array Implementation

```
2 1 3
2 2
```

```
4 4
7 7
5 5
6 6
```

```
<table>
<thead>
<tr>
<th>1 2 3 4 5 6 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>up weight</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>0 1 0 7 7 5 0</td>
</tr>
<tr>
<td>2 1 4</td>
</tr>
</tbody>
</table>
```
Union by Rank

Union(i, j : index) {
    //i and j are roots//
    wi := weight[i];
    wj := weight[j];
    if wi < wj then
        up[i] := j;
        weight[j] := wi + wj;
    else
        up[j] := i;
        weight[i] := wi + wj;
}
Kruskal's Algorithm Implementation (Revisited)

Kruskals():
    sort edges in increasing order of length \((e_1, e_2, e_3, ..., e_m)\).

    initialize disjoint sets.

    \(T := \{\}\). 

    for \(i = 1\) to \(m\)
        let \(e_i = (u, v)\).
        if find\((u) \neq \text{find}(v)\)
            union(find\((u)\), find\((v)\)).
            add \(e_i\) to \(T\).

    return \(T\).
Kruskal's Algorithm Running Time (Revisited)

- Assuming $|E| = m$ edges and $|V| = n$ nodes
- Sort edges: $O(m \log m)$
- Initialization: $O(n)$
- Finds: $O(2 \times m \times \log n) = O(m \log n)$
- Unions: $O(m)$

- Total running time: $O (m \log n + n + m \log n + m) = O (m \log n)$
  - note: $\log n$ and $\log m$ are within a constant factor of one another
Path Compression

• On a Find operation point all the nodes on the search path directly to the root.

![Diagram showing path compression](image-url)
Self-Adjustment Works

PC-Find(x)
Path Compression Exercise:

- Draw the resulting up tree after Find(e) with path compression.
Path Compression Find

PC-Find(i : index) {
    r := i;
    while up[r] ≠ 0 do //find root
        r := up[r];
    if i ≠ r then //compress path
        k := up[i];
        while k ≠ r do
            up[i] := r;
            i := k;
            k := up[k]
    return(r)
}
Disjoint Union / Find with Union By Rank and Path Comp.

• Worst case time complexity for a Union using Union by Rank is $\Theta(1)$ and for Find using Path Compression is $\Theta(\log n)$.

• Time complexity for $m \geq n$ operations on $n$ elements is $\Theta(m \log^* n)$
  – $\log^*$ is the number of times you need to apply the log function before you get to a number $\leq 1$
  – $\log^* n < 5$ for all reasonable $n$. Essentially constant time per operation!
Amortized Complexity

• For disjoint union / find with union by rank and path compression
  – average time per operation is essentially a constant
  – worst case time for a Find is $\Theta(\log n)$

• An individual operation can be costly, but over time the average cost per operation is not

• This means the bottleneck of Kruskal's actually becomes the sorting of the edges
Other Applications of Disjoint Sets

• Good for applications in need of clustering
  – cities connected by roads
  – cities belonging to the same country
  – connected components of a graph

• Forming equivalence classes (see textbook)

• Maze creation (see textbook)