Disjoint Sets and Union Find

Disjoint sets as a data structure, representation of disjoint sets, operations on disjoint sets, and the complexity of those operations

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Disjoint Sets and Union Find (Part 1)

Review: Sets

- *Set*: a collection of distinct objects
  - No duplicates
  - Order does not matter
- Set operations
  - Intersection, union, complement, etc.
- Set relationships
  - Subset (proper subset), superset (proper superset)
  - Testing for the property of being disjoint

Example

- Consider the following sets:
  - $A = \{1, 2\}$
  - $B = \{3, 4\}$
  - $C = \{8, 1\}$
- What is $A \cup B$?
  - $A \cup B = \{1, 2, 3, 4\}$
- What is $A \cap C$?
  - $A \cap C = \{1\}$
- Which sets are disjoint?
  - $A \cap B = \emptyset$
  - $B \cap C = \emptyset$
  - $A \cap C = \{1\}$
  - So sets A and B are disjoint and sets B and C are disjoint

Disjoint Sets

- A new data structure (hurrah!)
- A collection of n sets in which any two contain no common elements

- Written formally:

$$(\forall i, j \in \{1 \dots n\} \wedge i \neq j)(A_i \cap A_j = \emptyset)$$

- Basic operations:
  - *Find*: given an element, return the set it belongs to
    - Note, it can belong to at most one set
  - *Union*: merge two sets into one
    - Note: the union of two disjoint sets is still pairwise disjoint with all other sets, excluding the components of the union

Disjoint Sets Example

- Consider the following sets:
  - $A = \{1, 2\}$
  - $B = \{3, 4\}$
  - $C = \{8\}$
- Example operations:
  - find$(2) = A$
  - union$(a, b) =$ union$(a, b) = \{1, 2, 8\}$
    - Take the union of the two sets A and B such that $a \in A$ and $b \in B$
    - After the union, find$(2) =$ find(8)
    - After the union, there are only two sets in the collection: $A \cup B$ and C

Disjoing Sets: Union Find

- *Disjoint Set*: a collection of sets that are all disjoint
  - How can we represent this data structure?
    - Possibly with a tree?
  - Note the special features of this structure:
    - The union of all sets remains the same
    - The intersection of any two sets is always empty
- We only need to support two operations on this structure
  - `find()` – how could we implement this function?
  - `union()` – how could we implement this function?
- Quick find approach
- Quick union approach

Simple Solution: Set of Sets

- Organize the collection as a set of sets
- Each set is implemented using a normal set data structure, like a hash set, a binary search tree, etc.
- Operations:
  - `find(T t)`: search for `t` in every set
  - `union(T a, T b)`: assume that $a \in A$ and $b \in B$; add everything in B to A and discard B
- Do we really need a hash set or a binary search tree for `find` or `union`?

Quick Find Approach

- Number each item from 0 to $n-1$
- Maintain an array of n elements
  - Store the set that element i belongs to in `arr[i]`
- The complexity of find is trivial and $O(1)$
- What's the complexity of `union`?

item @ i	0	1	2	3
`arr[i]`	A	B	C	A

- Corresponds to the disjoint sets $A = \{0, 3\}, B = \{1\}$, and $C = \{2\}$
- As an example, suppose that $i \in A$ and $j \in B$, with $A \neq B$
  - Find all items in B, change ownership to A, and remove B
  - What's the complexity of this example?
    * $O(n)$
- After `union(0, 1)`: $A = \{0, 3, 1\}, C = \{2\}$, and B does not exist

item @ i	0	1	2	3
`arr[i]`	A	A	C	A

Quick-Find: Union

- The complexity of a single `union` is $O(n)$
- How many unions do we need for situations like maze generation
  - $n-1$, total time complexity is $O(n^2)$
- Can we improve the efficiency of the `union` if `find` isn't a concern?
  - Elements of the same set in one linked list?
  - Elements of the same set in one tree?

Quick Union with Trees

- Keep all elements of the same set in one tree
  - Represent the set with the tree root
- We continue to number each item 0 to $n-1$ and maintain an array of n elements
  - Store the parent of element i in `arr[i]`
  - If element i is the root, `arr[i] = -1`
  - `find(i)` returns the root of the tree that i belongs to
- As an example, consider the following collection of eight disjoint sets: $\{0\}, \{1\}, \{2\}, \{3\}, \{4\}, \{5\}, \{6\}, \{7\}$
  - We would represent this as a forest of eight trees, each containing only a root
  - Then `find(i)= i`
  - The array representation would be

i	`arr[i]`
0	-1
1	-1
2	-1
3	-1
4	-1
5	-1
6	-1
7	-1

Tree Representation

- *Union*: merge two trees
  - (Naive) union(r_1, r_2): Let r_1 and r_2 be the roots of two trees; add r_2, as a child, to r_1 – then r_1 is the new root of the merged tree
  - union(i, j): for any element i and j, is equivalent to union(r_1, r_2)
- *Find*: walk up the tree until the root is reached and report the ID of the root

Tree: Union-Find Example

Here, we use the same collection of eight disjoint sets that we used in Quick Union with Trees.

- union$(4, 5)$
  - Graphical representation:

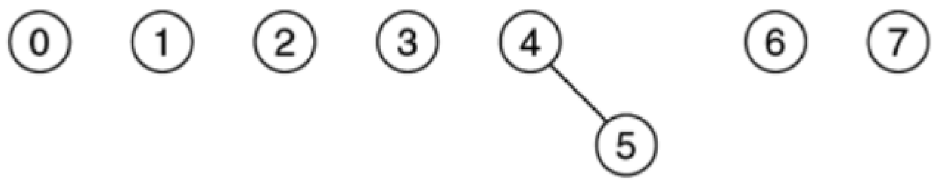

Figure 1: Tree representation of disjoint sets after performing union$(4, 5)$

  - Tabular representation:

i	`arr[i]`
0	-1
1	-1
2	-1
3	-1
4	-1
5	4
6	-1
7	-1

- union$(6, 7)$

- Graphical representation:

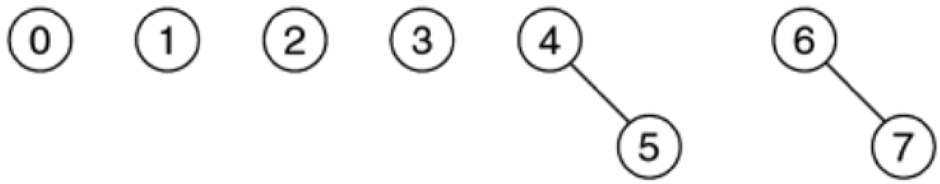

Figure 2: Tree representation of disjoint sets after performing union$(6, 7)$

- Tabular representation:

i	`arr[i]`
0	-1
1	-1
2	-1
3	-1
4	-1
5	4
6	-1
7	6

- union$(4, 7)$
  - Graphical representation:

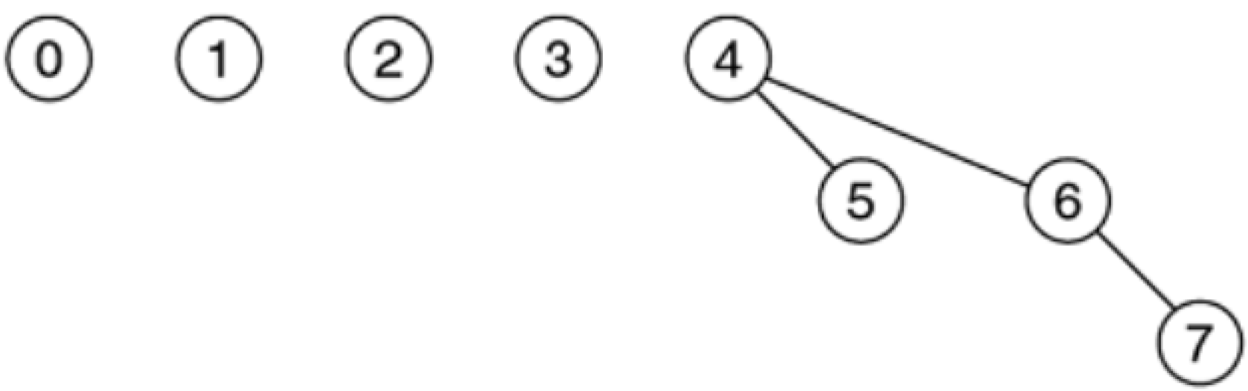

Figure 3: Tree representation of disjoint sets after performing union$(4, 7)$

- Tabular representation:

i	`arr[i]`
0	-1
1	-1
2	-1
3	-1
4	-1
5	4
6	4
7	6

Practice One

- Start with 10 one-element sets (so 10 single-node trees)

0	1	2	3	4	5	6	7	8	9
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

- Try union$(1, 2)$, union$(8, 6)$, find(6), and find(1)
- Then try union$(8, 7)$, union$(2, 4)$, union$(3, 6)$, and find(6)
- Draw the trees and fill the table

Practice Two

- Start with 10 one-element sets (so 10 single-node trees)

0	1	2	3	4	5	6	7	8	9
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

- Try union$(1, 2)$, union$(3, 1)$, union$(5, 2)$, and union$(6, 3)$

- Draw the trees and fill the table

Complexity

- `find`
  - Walk backwards until the root is encountered
  - So it's $O(\text{height})$
  - Worst case is then $O(n)$
- `union`
  - $O(1)$ if the root is already known
  - $O(n)$ including the time to find the root
- How can we improve the efficiency of these methods?

Complexity As of Now

- Worst case scenarios with n initial sets

Approach	Union	Find
Set of sets	$O(n)$	$O(n)$
Quick find	$O(n)$	$O(1)$
Tree (naive)	$O(1)^*$	$O(n)$

- *: if the roots are given; if the roots are not given, then $O(n)$ time since we must find the root

Improved Union

- Idea: we can do union-by-rank
  - Attach the smaller tree to the bigger one (union-by-size)
    - Break the tie by using the root of the first element as the new root
  - Avoid constructing tall trees

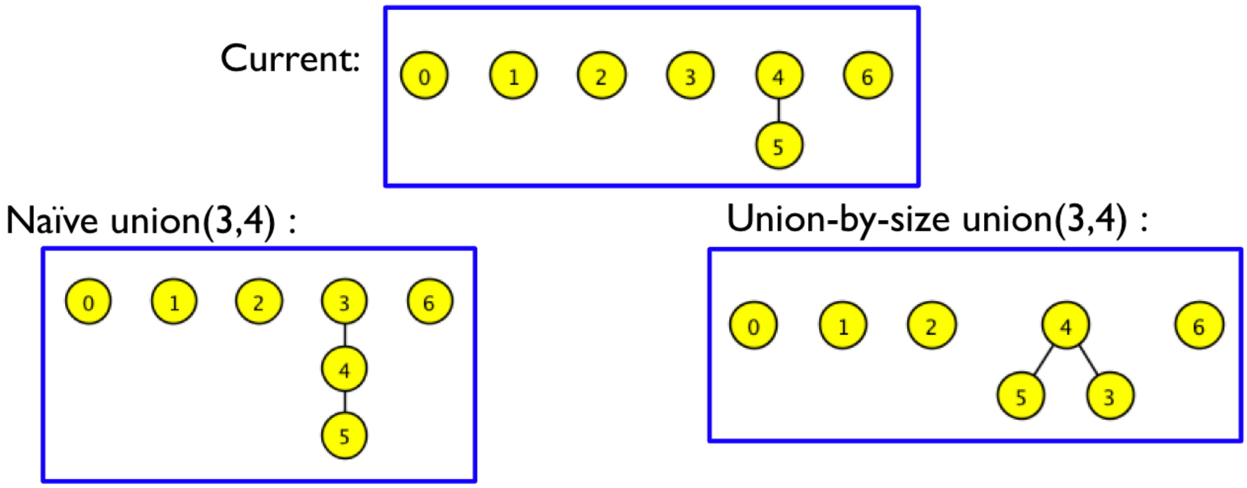

Figure 4: Union by rank example

- `arr[i]` representation:
  - Case where (≥ 0): parent of element of i
  - Case where (< 0): element i is the root of the tree and the size of the tree is `abs(arr[i])`

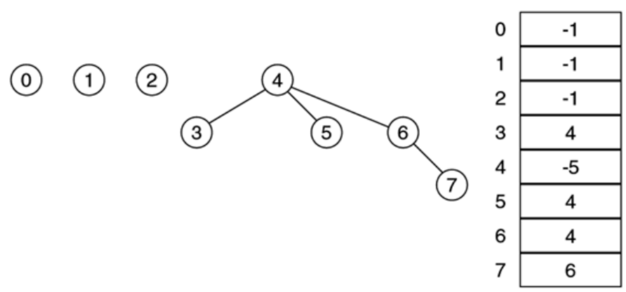

Figure 5: The forest formed by union-by-size, with the sizes encoded as negative numbers

Practice Three

- Start with 10 one-element sets (so 10 single-node trees)

0	1	2	3	4	5	6	7	8	9
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

- Using union-by-size, try union$(1, 2)$, union$(3, 1)$, union$(5, 2)$, and union$(6, 3)$
- Draw the trees and fill the table

Complexity Revisited

- Worst case scenarios with n initial sets

Approach	Union	Find
Set of sets	$O(n)$	$O(n)$
Quick find	$O(n)$	$O(1)$
Tree (naive)	$O(n)^*$	$O(n)$
Tree (rank union and naive find)	$O(\log(n))^*$	$O(\log(n))$

- *: includes time to find the root; it's $O(1)$ if the roots are given