

## 9 Union Find

**Union Find Data Structure  $\mathcal{P}$ :** Maintains a partition of **disjoint** sets over elements.

- ▶  **$\mathcal{P}$ . makeset( $x$ ):** Given an element  $x$ , adds  $x$  to the data-structure and creates a singleton set that contains only this element. Returns a locator/handle for  $x$  in the data-structure.
- ▶  **$\mathcal{P}$ . find( $x$ ):** Given a handle for an element  $x$ ; find the set that contains  $x$ . Returns a representative/identifier for this set.
- ▶  **$\mathcal{P}$ . union( $x, y$ ):** Given two elements  $x$ , and  $y$  that are currently in sets  $S_x$  and  $S_y$ , respectively, the function replaces  $S_x$  and  $S_y$  by  $S_x \cup S_y$  and returns an identifier for the new set.

## 9 Union Find

### Applications:

- ▶ Keep track of the connected components of a dynamic graph that changes due to insertion of nodes and edges.
- ▶ Kruskals Minimum Spanning Tree Algorithm

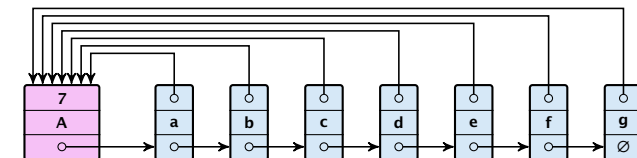
## 9 Union Find

### Algorithm 16 Kruskal-MST( $G = (V, E), w$ )

```
1:  $A \leftarrow \emptyset$ ;  
2: for all  $v \in V$  do  
3:    $v.\text{set} \leftarrow \mathcal{P}.\text{makeset}(v.\text{label})$   
4: sort edges in non-decreasing order of weight  $w$   
5: for all  $(u, v) \in E$  in non-decreasing order do  
6:   if  $\mathcal{P}.\text{find}(u.\text{set}) \neq \mathcal{P}.\text{find}(v.\text{set})$  then  
7:      $A \leftarrow A \cup \{(u, v)\}$   
8:      $\mathcal{P}.\text{union}(u.\text{set}, v.\text{set})$ 
```

## List Implementation

- ▶ The elements of a set are stored in a list; each node has a backward pointer to the head.
- ▶ The head of the list contains the identifier for the set and a field that stores the **size** of the set.



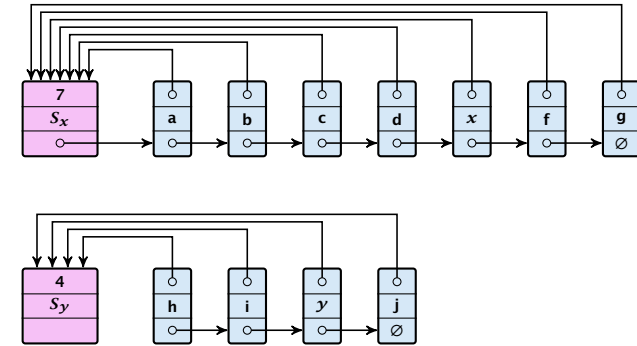
- ▶ **makeset( $x$ )** can be performed in constant time.
- ▶ **find( $x$ )** can be performed in constant time.

## List Implementation

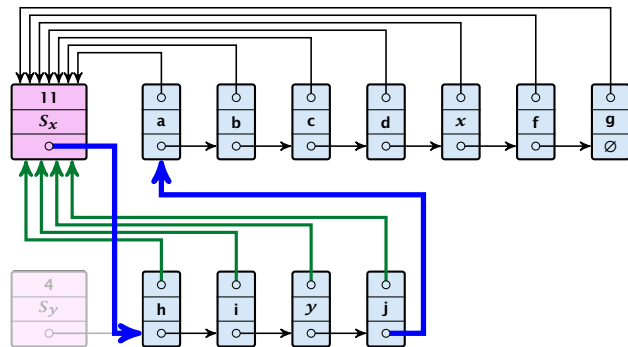
### union( $x, y$ )

- ▶ Determine sets  $S_x$  and  $S_y$ .
- ▶ Traverse the smaller list (say  $S_y$ ), and change all backward pointers to the head of list  $S_x$ .
- ▶ Insert list  $S_y$  at the head of  $S_x$ .
- ▶ Adjust the size-field of list  $S_x$ .
- ▶ Time:  $\min\{|S_x|, |S_y|\}$ .

## List Implementation



## List Implementation



## List Implementation

### Running times:

- ▶  $\text{find}(x)$ : constant
- ▶  $\text{makeset}(x)$ : constant
- ▶  $\text{union}(x, y)$ :  $\mathcal{O}(n)$ , where  $n$  denotes the number of elements contained in the set system.

## List Implementation

### Lemma 1

The list implementation for the ADT union find fulfills the following amortized time bounds:

- ▶  $\text{find}(x)$ :  $\mathcal{O}(1)$ .
- ▶  $\text{makeset}(x)$ :  $\mathcal{O}(\log n)$ .
- ▶  $\text{union}(x, y)$ :  $\mathcal{O}(1)$ .

## The Accounting Method for Amortized Time Bounds

- ▶ There is a bank account for every element in the data structure.
- ▶ Initially the balance on all accounts is zero.
- ▶ Whenever for an operation the amortized time bound exceeds the actual cost, the difference is credited to some bank accounts of elements involved.
- ▶ Whenever for an operation the actual cost exceeds the amortized time bound, the difference is charged to bank accounts of some of the elements involved.
- ▶ If we can find a charging scheme that guarantees that balances always stay positive the amortized time bounds are proven.

## List Implementation

- ▶ For an operation whose actual cost exceeds the amortized cost we charge the **excess** to the elements involved.
- ▶ In total we will charge at most  $\mathcal{O}(\log n)$  to an element (regardless of the request sequence).
- ▶ For each element a makeset operation occurs as the first operation involving this element.
- ▶ We inflate the amortized cost of the makeset-operation to  $\Theta(\log n)$ , i.e., at this point we fill the bank account of the element to  $\Theta(\log n)$ .
- ▶ Later operations charge the account but the balance never drops below zero.

## List Implementation

**makeset(x)**: The actual cost is  $\mathcal{O}(1)$ . Due to the cost inflation the amortized cost is  $\mathcal{O}(\log n)$ .

**find(x)**: For this operation we define the amortized cost and the actual cost to be the same. Hence, this operation does not change any accounts. Cost:  $\mathcal{O}(1)$ .

**union(x, y)**:

- ▶ If  $S_x = S_y$  the cost is constant; no bank accounts change.
- ▶ Otw. the actual cost is  $\mathcal{O}(\min\{|S_x|, |S_y|\})$ .
- ▶ Assume wlog. that  $S_x$  is the smaller set; let  $c$  denote the hidden constant, i.e., the actual cost is at most  $c \cdot |S_x|$ .
- ▶ Charge  $c$  to every element in set  $S_x$ .

## List Implementation

### Lemma 2

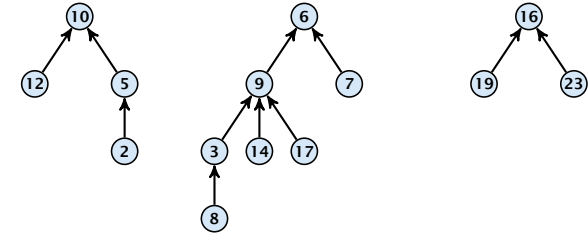
An element is charged at most  $\lceil \log_2 n \rceil$  times, where  $n$  is the total number of elements in the set system.

### Proof.

Whenever an element  $x$  is charged the number of elements in  $x$ 's set doubles. This can happen at most  $\lceil \log n \rceil$  times.  $\square$

## Implementation via Trees

- ▶ Maintain nodes of a set in a tree.
- ▶ The root of the tree is the label of the set.
- ▶ Only pointer to parent exists; we cannot list all elements of a given set.
- ▶ Example:



Set system  $\{2, 5, 10, 12\}$ ,  $\{3, 6, 7, 8, 9, 14, 17\}$ ,  $\{16, 19, 23\}$ .

## Implementation via Trees

### makeset( $x$ )

- ▶ Create a singleton tree. Return pointer to the root.
- ▶ Time:  $\mathcal{O}(1)$ .

### find( $x$ )

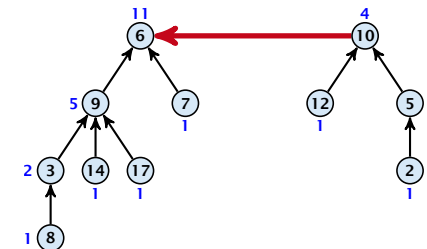
- ▶ Start at element  $x$  in the tree. Go upwards until you reach the root.
- ▶ Time:  $\mathcal{O}(\text{level}(x))$ , where  $\text{level}(x)$  is the distance of element  $x$  to the root in its tree. **Not constant.**

## Implementation via Trees

To support union we store the size of a tree in its root.

### union( $x, y$ )

- ▶ Perform  $a \leftarrow \text{find}(x)$ ;  $b \leftarrow \text{find}(y)$ . Then:  $\text{link}(a, b)$ .
- ▶  $\text{link}(a, b)$  attaches the **smaller** tree as the child of the larger.
- ▶ In addition it updates the size-field of the new root.



- ▶ Time: constant for  $\text{link}(a, b)$  plus two find-operations.

## Implementation via Trees

### Lemma 3

The running time (non-amortized!!!) for  $\text{find}(x)$  is  $\mathcal{O}(\log n)$ .

### Proof.

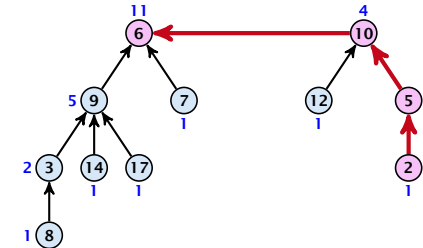
- ▶ When we attach a tree with root  $c$  to become a child of a tree with root  $p$ , then  $\text{size}(p) \geq 2 \text{size}(c)$ , where  $\text{size}$  denotes the value of the size-field right after the operation.
- ▶ After that the value of  $\text{size}(c)$  stays fixed, while the value of  $\text{size}(p)$  may still increase.
- ▶ Hence, at any point in time a tree fulfills  $\text{size}(p) \geq 2 \text{size}(c)$ , for any pair of nodes  $(p, c)$ , where  $p$  is a parent of  $c$ .

□

## Path Compression

### $\text{find}(x)$ :

- ▶ Go upward until you find the root.
- ▶ Re-attach all visited nodes as children of the root.
- ▶ Speeds up successive find-operations.

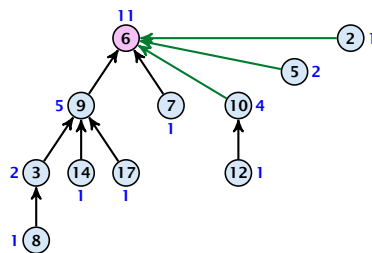


- ▶ Note that the size-fields now only give an upper bound on the size of a sub-tree.

## Path Compression

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One could change the algorithm to update the size-fields. This could be done without asymptotically affecting the running time.

However, the only size-field that is actually required is the field at the root, which is always correct.

We will only use the other size-fields for the proof of Theorem 6.

- ▶ Note that the size-fields now only give an upper bound on the size of a sub-tree.

## Path Compression

Asymptotically the cost for a find-operation does not increase due to the path compression heuristic.

However, for a worst-case analysis there is no improvement on the running time. It can still happen that a find-operation takes time  $\mathcal{O}(\log n)$ .

## Amortized Analysis

### Definitions:

- ▶  $\text{size}(v)$  := the number of nodes that were in the sub-tree rooted at  $v$  when  $v$  became the child of another node (or the number of nodes if  $v$  is the root).

Note that this is the same as the size of  $v$ 's subtree in the case that there are no find-operations.

- ▶  $\text{rank}(v) := \lfloor \log(\text{size}(v)) \rfloor$ .
- ▶  $\Rightarrow \text{size}(v) \geq 2^{\text{rank}(v)}$ .

### Lemma 4

The rank of a parent must be strictly larger than the rank of a child.

## Amortized Analysis

### Lemma 5

There are at most  $n/2^s$  nodes of rank  $s$ .

### Proof.

- ▶ Let's say a node  $v$  sees node  $x$  if  $v$  is in  $x$ 's sub-tree at the time that  $x$  becomes a child.
- ▶ A node  $v$  sees at most one node of rank  $s$  during the running time of the algorithm.
- ▶ This holds because the rank-sequence of the roots of the different trees that contain  $v$  during the running time of the algorithm is a strictly increasing sequence.
- ▶ Hence, every node sees at most one rank  $s$  node, but every rank  $s$  node is seen by at least  $2^s$  different nodes.  $\square$

## Amortized Analysis

We define

$$\text{tow}(i) := \begin{cases} 1 & \text{if } i = 0 \\ 2^{\text{tow}(i-1)} & \text{otw.} \end{cases} \quad \text{tow}(i) = 2^{2^{2^{\dots^2}}} \text{ } i \text{ times}$$

and

$$\log^*(n) := \min\{i \mid \text{tow}(i) \geq n\}.$$

### Theorem 6

Union find with path compression fulfills the following amortized running times:

- ▶  $\text{makeset}(x) : \mathcal{O}(\log^*(n))$
- ▶  $\text{find}(x) : \mathcal{O}(\log^*(n))$
- ▶  $\text{union}(x, y) : \mathcal{O}(\log^*(n))$

## Amortized Analysis

In the following we assume  $n \geq 2$ .

### rank-group:

- ▶ A node with rank  $\text{rank}(v)$  is in rank group  $\log^*(\text{rank}(v))$ .
- ▶ The rank-group  $g = 0$  contains only nodes with rank 0 or rank 1.
- ▶ A rank group  $g \geq 1$  contains ranks  $\text{tow}(g-1) + 1, \dots, \text{tow}(g)$ .
- ▶ The maximum non-empty rank group is  $\log^*(\lfloor \log n \rfloor) \leq \log^*(n) - 1$  (which holds for  $n \geq 2$ ).
- ▶ Hence, the total number of rank-groups is at most  $\log^* n$ .

## Amortized Analysis

### Accounting Scheme:

- ▶ create an account for every find-operation
- ▶ create an account for every node  $v$

The cost for a find-operation is equal to the length of the path traversed. We charge the cost for going from  $v$  to  $\text{parent}[v]$  as follows:

- ▶ If  $\text{parent}[v]$  is the root we charge the cost to the find-account.
- ▶ If the group-number of  $\text{rank}(v)$  is the same as that of  $\text{rank}(\text{parent}[v])$  (before starting path compression) we charge the cost to the node-account of  $v$ .
- ▶ Otherwise we charge the cost to the find-account.

## Amortized Analysis

### Observations:

- ▶ A find-account is charged at most  $\log^*(n)$  times (once for the root and at most  $\log^*(n) - 1$  times when increasing the rank-group).
- ▶ After a node  $v$  is charged its parent-edge is re-assigned. The rank of the parent strictly increases.
- ▶ After some charges to  $v$  the parent will be in a larger rank-group.  $\Rightarrow v$  will **never** be charged again.
- ▶ The total charge made to a node in rank-group  $g$  is at most  $\text{tow}(g) - \text{tow}(g - 1) - 1 \leq \text{tow}(g)$ .

## Amortized Analysis

### What is the total charge made to nodes?

- ▶ The total charge is at most

$$\sum_g n(g) \cdot \text{tow}(g) ,$$

where  $n(g)$  is the number of nodes in group  $g$ .

## Amortized Analysis

For  $g \geq 1$  we have

$$\begin{aligned} n(g) &\leq \sum_{s=\text{tow}(g-1)+1}^{\text{tow}(g)} \frac{n}{2^s} = \frac{n}{2^{\text{tow}(g-1)+1}} \sum_{s=0}^{\text{tow}(g)-\text{tow}(g-1)-1} \frac{1}{2^s} \\ &\leq \frac{n}{2^{\text{tow}(g-1)+1}} \sum_{s=0}^{\infty} \frac{1}{2^s} \leq \frac{n}{2^{\text{tow}(g-1)+1}} \cdot 2 \\ &\leq \frac{n}{2^{\text{tow}(g-1)}} = \frac{n}{\text{tow}(g)} . \end{aligned}$$

Hence,

$$\sum_g n(g) \text{tow}(g) \leq n(0) \text{tow}(0) + \sum_{g \geq 1} n(g) \text{tow}(g) \leq n \log^*(n)$$

## Amortized Analysis

Without loss of generality we can assume that all **makeset**-operations occur at the start.

This means if we inflate the cost of **makeset** to  $\log^* n$  and add this to the node account of  $v$  then the balances of all node accounts will sum up to a positive value (this is sufficient to obtain an amortized bound).

## Amortized Analysis

The analysis is not tight. In fact it has been shown that the amortized time for the union-find data structure with path compression is  $\mathcal{O}(\alpha(m, n))$ , where  $\alpha(m, n)$  is the inverse Ackermann function which grows a lot lot slower than  $\log^* n$ . (Here, we consider the average running time of  $m$  operations on at most  $n$  elements).

There is also a lower bound of  $\Omega(\alpha(m, n))$ .

## Amortized Analysis

$$A(x, y) = \begin{cases} y + 1 & \text{if } x = 0 \\ A(x - 1, 1) & \text{if } y = 0 \\ A(x - 1, A(x, y - 1)) & \text{otw.} \end{cases}$$

$$\alpha(m, n) = \min\{i \geq 1 : A(i, \lfloor m/n \rfloor) \geq \log n\}$$

- ▶  $A(0, y) = y + 1$
- ▶  $A(1, y) = y + 2$
- ▶  $A(2, y) = 2y + 3$
- ▶  $A(3, y) = 2^{y+3} - 3$
- ▶  $A(4, y) = \underbrace{2^{2^{2^{\dots}}}}_{y+3 \text{ times}} - 3$

## Union Find

### Bibliography

- [CLRS90a] Thomas H. Cormen, Charles E. Leiserson, Ron L. Rivest: *Introduction to Algorithms (1st ed.)*, MIT Press and McGraw-Hill, 1990
- [CLRS90b] Thomas H. Cormen, Charles E. Leiserson, Ron L. Rivest, Clifford Stein: *Introduction to Algorithms (2nd ed.)*, MIT Press and McGraw-Hill, 2001
- [CLRS90c] Thomas H. Cormen, Charles E. Leiserson, Ron L. Rivest, Clifford Stein: *Introduction to Algorithms (3rd ed.)*, MIT Press and McGraw-Hill, 2009
- [AHU74] Alfred V. Aho, John E. Hopcroft, Jeffrey D. Ullman: *The Design and Analysis of Computer Algorithms*, Addison-Wesley, 1974

Union find data structures are discussed in Chapter 21 of [CLRS90b] and [CLRS90c] and in Chapter 22 of [CLRS90a]. The analysis of union by rank with path compression can be found in [CLRS90a] but neither in [CLRS90b] nor in [CLRS90c]. The latter books contains a more involved analysis that gives a better bound than  $\mathcal{O}(\log^* n)$ .

A description of the  $\mathcal{O}(\log^*)$ -bound can also be found in Chapter 4.8 of [AHU74].