



南京大學

NANJING UNIVERSITY

Introduction to

Algorithm Design and Analysis

[10] Union-Find



Yu Huang

<http://cs.nju.edu.cn/yuhuang>
Institute of Computer Software
Nanjing University



In the Last Class

- **Hashing**
 - Basic idea
- **Collision handling for hashing**
 - Closed address
 - Open address
- **Amortized analysis**
 - Array doubling
 - Stack operations
 - Binary counter



Union-Find

- **Dynamic Equivalence Relation**
 - Examples
 - Definitions
 - Brute force implementations
- **Disjoint Set**
 - Straightforward Union-Find
 - Weighted Union + Straightforward Find
 - Weighted Union + Path Compressing Find



Minimum Spanning Tree

- **Kruskal's algorithm, greedy strategy:**
 - Select one edge
 - With the minimum weight
 - Not in the tree
 - Evaluate this edge
 - This edge will **NOT** result in a cycle
- **Critical issue:**
 - How to know **"NO CYCLE"**?



Guess My Number – an Example

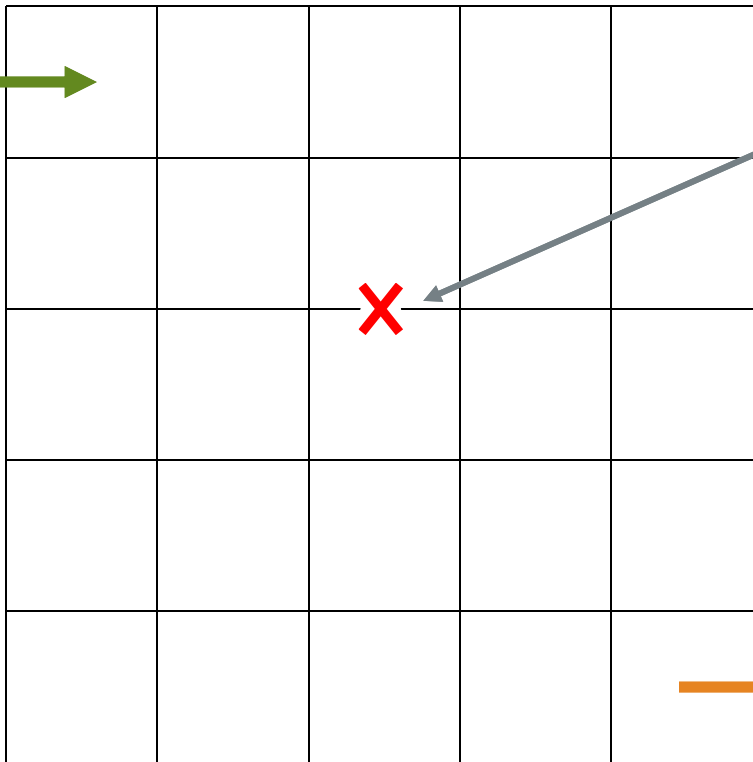
- I pick a secret positive integer x
- In each round, you write a list of numbers
 - You list at most x numbers
 - I told you the position of x
- You must guarantee to win
 - What is the least number of rounds in the worst case?

You	Me
1	It's bigger than 1.
4, 42	It's between 4 and 42.
8, 15, 16, 23, 30	It's between 8 and 15.
9, 10, 11, 12, 13, 14	It's 11; you win!



Maze Generation

inlet



Select a wall to pull down randomly

If i and j are in same *equivalence class*, then select another wall to pull down.

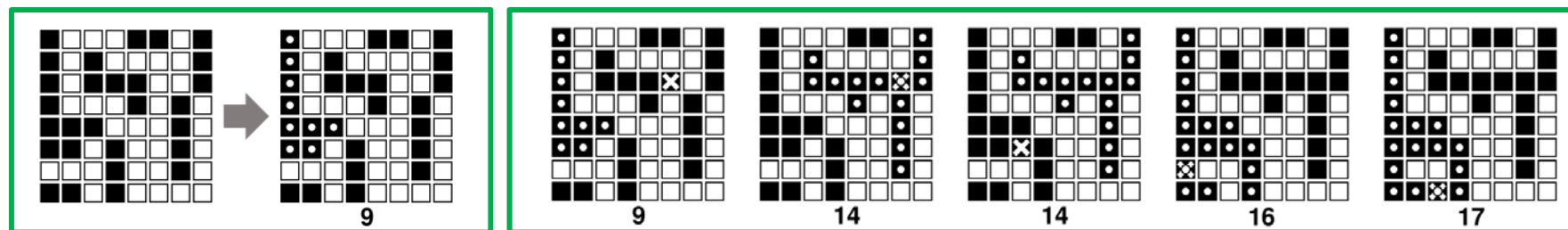
Otherwise, joint the two classes into one.

The maze is complete when the inlet and outlet are in one equivalence class.



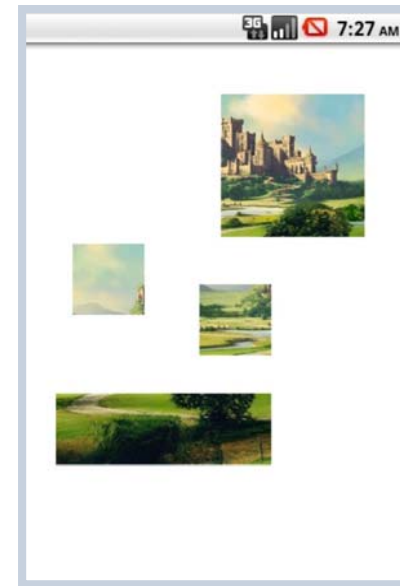
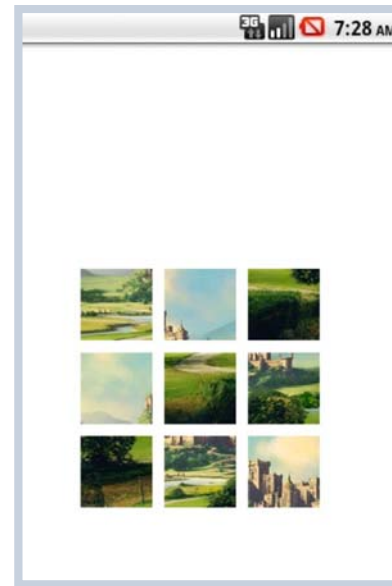
Black Pixels

- **Maximum black pixel component**
 - Let α be the size of the component
- **Color one pixel black**
 - How α changes?
 - How to choose the pixel, to accelerate the change in α



Jigsaw Puzzle

- Multiple pieces may be glued together
- From “one player” to “two players”
 - Each group can only be moved in a mutual exclusive way
 - How to decide the relation of “in the same group”



Dynamic Equivalence Relations

- **Equivalence**
 - Reflexive, symmetric, transitive
 - Equivalent classes forming a **partition**
- **Dynamic equivalence relation**
 - Changing in the process of computation
 - **IS** instruction: *yes* or *no* (in the same equivalence class)
 - **MAKE** instruction: combining two equivalent classes, by relating two unrelated elements, and influencing the results of subsequent IS instructions.
 - Starting as equality relation



Implementation: How to Measure

- The number of basic operations for processing a sequence of m **MAKE** and/or **IS** instructions on a set S with n elements.
- An Example: $S=\{1,2,3,4,5\}$

- 0. [create] $\{\{1\}, \{2\}, \{3\}, \{4\}, \{5\}\}$
- 1. **IS** $2 \equiv 4?$ No
- 2. **IS** $3 \equiv 5?$ No
- 3. **MAKE** $3 \equiv 5.$ $\{\{1\}, \{2\}, \{3,5\}, \{4\}\}$
- 4. **MAKE** $2 \equiv 5.$ $\{\{1\}, \{2,3,5\}, \{4\}\}$
- 5. **IS** $2 \equiv 3?$ Yes
- 6. **MAKE** $4 \equiv 1.$ $\{\{1,4\}, \{2,3,5\}\}$
- 7. **IS** $2 \equiv 4?$ No



Union-Find based Implementation

- **The maze problem**
 - Each cell as a set
 - Randomly delete a wall and **union** two cells
 - Loop until you **find** the inlet and outlet are in one equivalent class
- **The Kruskal algorithm**
 - Each node as a set
 - Choose the least weight edge (u,v)
 - **Find** whether u and v are in the same equivalent class
 - If not, add the edge and **union** the two nodes



Implementation: Choices

- **Matrix (relation matrix)**
 - Space in $\Theta(n^2)$, and worst-case cost in $O(mn^2)$ (mainly for row copying for MAKE)
- **Array (for equivalence class ID)**
 - Space in $\Theta(n)$, and worst-case cost in $O(mn)$ (mainly for search and change for MAKE)
- **Disjoint Set**
 - A collection of disjoint sets, supporting *Union* and *Find* operations
 - There is no way to traverse all the elements in one set



Union-Find ADT

- **Constructor:** **Union-Find** `create(int n)`
 - `sets=create(n)` refers to a newly created group of sets $\{1\}, \{2\}, \dots, \{n\}$ (*n* singletons)
- **Access Function:** **int** `find(UnionFind sets, e)`
 - `find(sets, e)=<e>`
- **Manipulation Procedures**
 - **void** `makeSet(UnionFind sets, int e)`
 - **void** `union(UnionFind sets, int s, int t)`

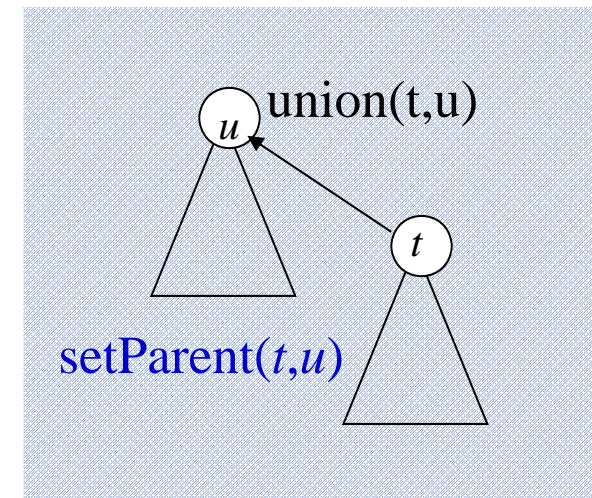
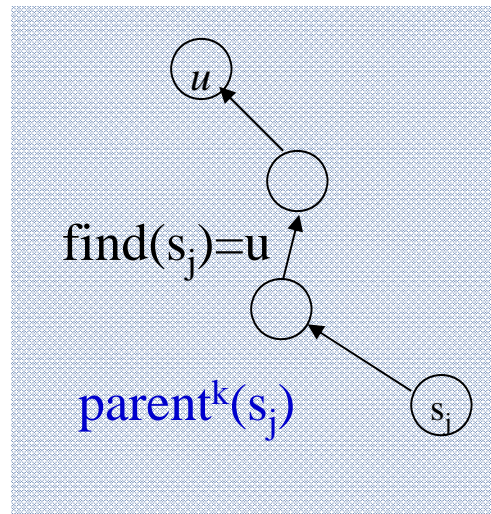


Using Union-Find (as inTree)

- **IS** $s_i \equiv s_j$:
 - $t = \text{find}(s_i);$
 - $u = \text{find}(s_j);$
 - $(t == u)?$
- **MAKE** $s_i \equiv s_j$:
 - $t = \text{find}(s_i);$
 - $u = \text{find}(s_j);$
 - $\text{union}(t, u);$

implementation by inTree

create(n): sequence of makeNode



Union-Find Program

- A **union-find program of length m**
 - is (a *create*(n) operation followed by) a sequence of m union and/or find operations in any order
- A union-find program is considered an input
 - The object on which the analysis is conducted
- The measure: number of accesses to the ***parent***
 - assignments: for union operations
 - lookups: for find operations

} **link operation**



Worst-case Analysis for Union-Find Program

- Assuming each lookup/assignment take $O(1)$.
- Each makeSet or union does one assignment, and each find does $d+1$ lookups, where d is the depth of the node.

1. Union(1,2)
2. Union(2,3)
⋮
n-1. Union(n-1,n)
n. Find(1)
⋮
m. Find(1)

Example

The sequence of *Union* makes a chain of length $n-1$, which is the tree with the largest height

operations done:

$$n + (n-1) + (m-n+1)n$$

$$\Theta(mn)$$

Find(1) needs n array lookups



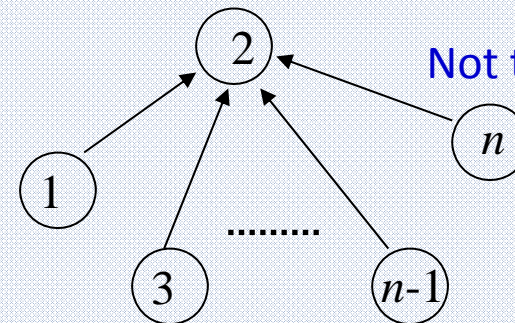
Weighted Union: for Short Trees

- **Weighted union (*wUnion*)**
 - always have the tree with **fewer nodes** as subtree

To keep the *Union* valid,
each *Union* operation is
replaced by:

```
t=find(i);  
u=find(j);  
union(t,u)
```

The order of (t,u)
satisfying the
requirement

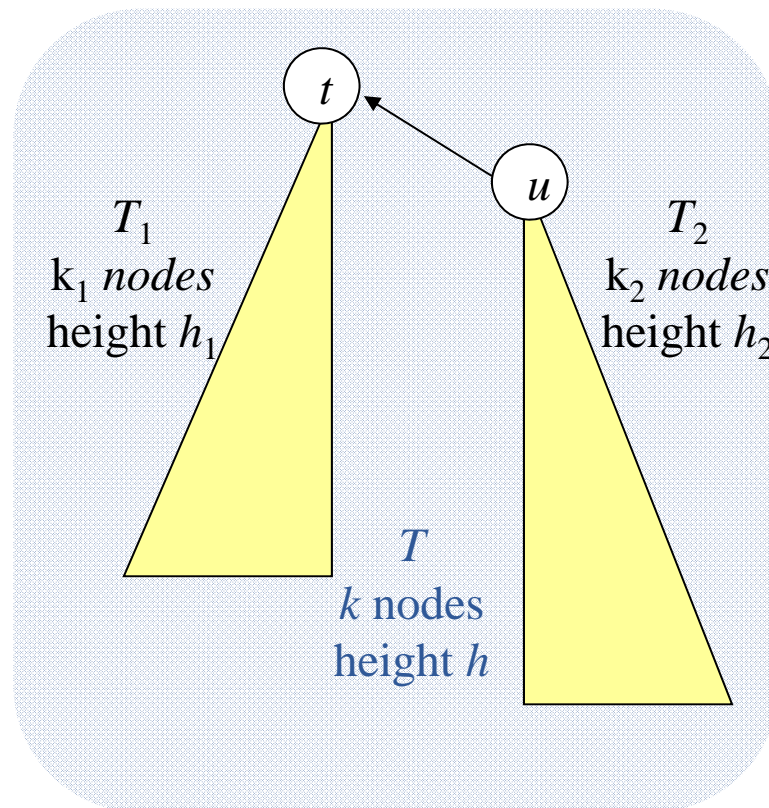


Tree made by wUnion

Cost for the program:
 $n+3(n-1)+2(m-n+1)$

Upper Bound of Tree Height

- After any sequence of *Union* instructions, implemented by *wUnion*, any tree that has k nodes will have height at most $\lfloor \lg k \rfloor$
- Proof by induction on k :
 - base case: $k=1$, the height is 0.
 - by inductive hypothesis:
 - $h_1 \leq \lfloor \lg k_1 \rfloor$, $h_2 \leq \lfloor \lg k_2 \rfloor$
 - $h = \max(h_1, h_2 + 1)$, $k = k_1 + k_2$
 - if $h = h_1$, $h \leq \lfloor \lg k_1 \rfloor \leq \lfloor \lg k \rfloor$
 - if $h = h_2 + 1$, note: $k_2 \leq k/2$
so, $h_2 + 1 \leq \lfloor \lg k_2 \rfloor + 1 \leq \lfloor \lg k \rfloor$



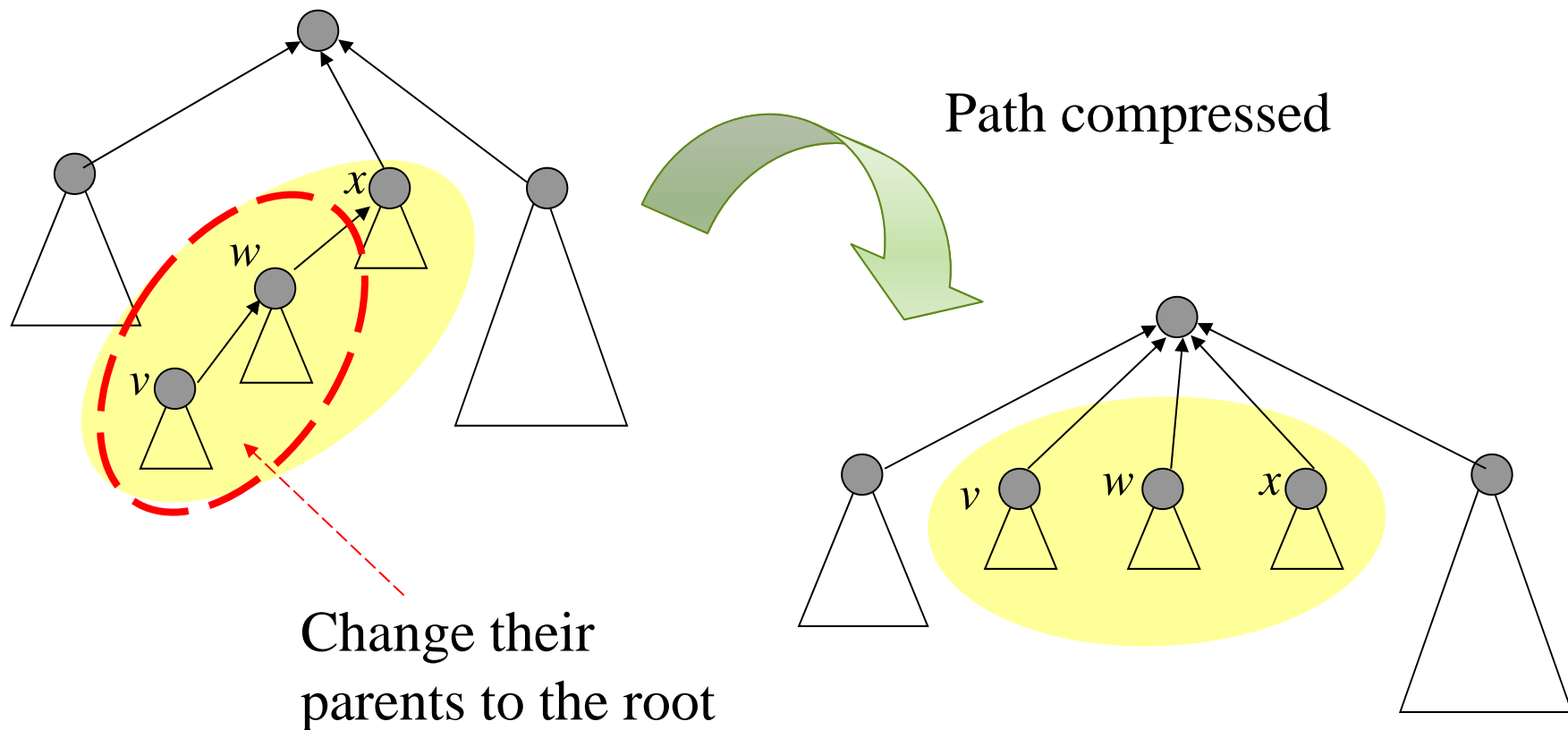
Upper Bound for Union-Find Program

- A Union-Find program of size m , on a set of n elements, performs $O(n+m\log n)$ link operations in the worst case if *wUnion* and straight *find* are used
- Proof:
 - At most $n-1$ *wUnion* can be done, building a tree with height at most $\lfloor \log n \rfloor$,
 - Then, each *find* costs at most $\lfloor \log n \rfloor + 1$.
 - Each *wUnion* costs in $O(1)$, so, the upper bound on the cost of any combination of m *wUnion*/*find* operations is the cost of m *find* operations, that is $m(\lfloor \log n \rfloor + 1) \in O(n+m\log n)$

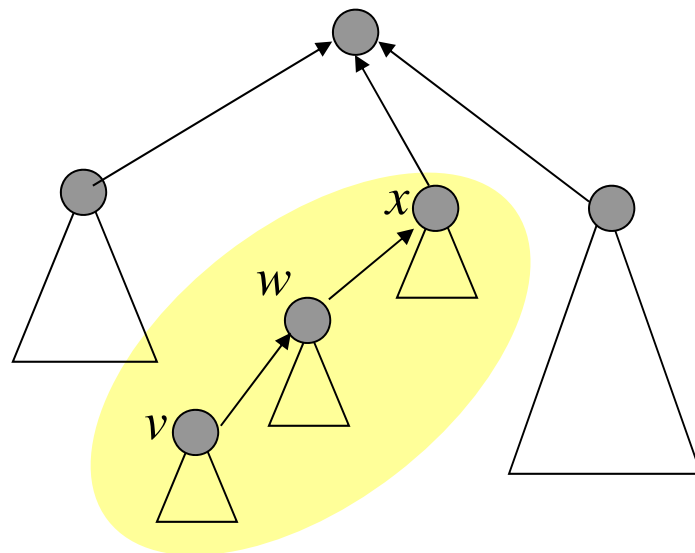
There do exist programs requiring $\Omega(n+(m-n)\log n)$ steps.



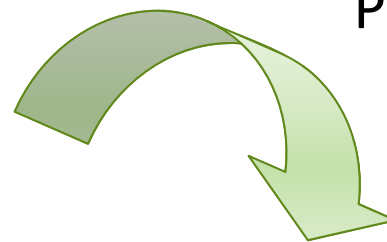
Path Compression



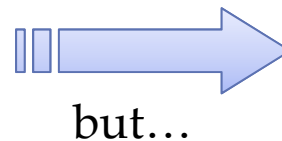
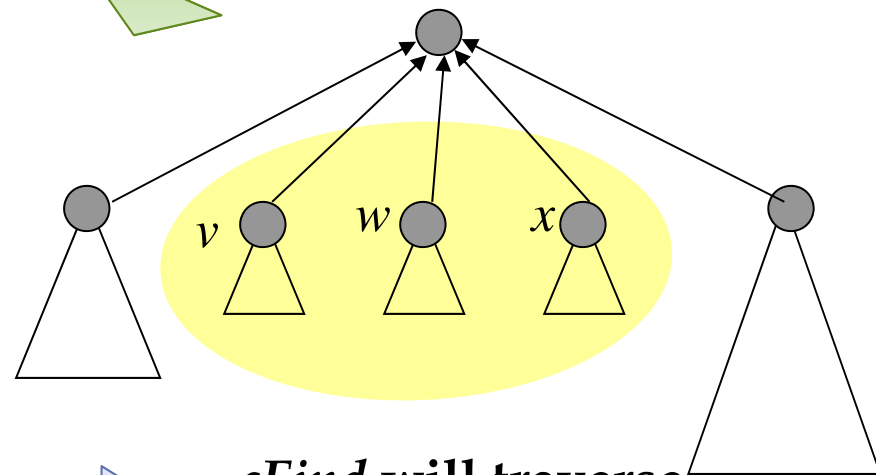
Challenges for the Analysis



cFind does **twice as many** link operations as the *find* does for a given node in a given tree.



Path compressed



cFind will traverse **shorter** paths

Analysis: the Basic Idea

- **cFind may be an expensive operation**
 - in the case that $\text{find}(i)$ is executed and the node i has great depth.
- **However, such cFind can be executed only for limited times**
 - Path compressions depends on previous unions
- **So, *amortized analysis* applies**



Co-Strength of *wUnion* and *cFind*

- $O((n+m)\log^*(n))$

- Link operations for a *Union-Find* program of length m on a set of n elements is in the worst case.
- Implemented with *wUnion* and *cFind*

What's $\log^*(n)$?

- Define the function H as following:

$$\begin{cases} H(0) = 1 \\ H(i) = 2^{H(i-1)} \text{ for } i > 0 \end{cases}$$

- Then, $\log^*(j)$ for $j \geq 1$ is defined as:
$$\log^*(j) = \min\{k \mid H(k) \geq j\}$$



Definitions with a *Union-Find* Program P

- **Forest F** : the forest constructed by the sequence of *union* instructions in P , assuming:
 - $wUnion$ is used;
 - the *finds* in the P are ignored
- **Height** of a node v in any tree: the height of the subtree rooted at v
- **Rank** of v : the height of v *in F*

Note: *cFind* changes the height of a node, but the rank for any node is invariable.



Constraints on Ranks in F

- The upper bound of the number of nodes with rank r ($r \geq 0$) is $\frac{n}{2^r}$
 - Remember that the height of the tree built by $wUnion$ is at most $\lfloor \lg n \rfloor$, which means the subtree of height r has at least 2^r nodes.
 - The subtrees with root at rank r are disjoint.
- There are at most $\lfloor \lg n \rfloor$ different ranks.
 - There are altogether n elements in S , that is, n nodes in F .



Increasing Sequence of Ranks

- The ranks of the nodes on a path from a leaf to a root of a tree in F form a strictly increasing sequence.
- When a *cFind* operation changes the parent of a node, the new parent has higher rank than the old parent of that node.
 - Note: the new parent was an ancestor of the previous parent.



A Function Growing Extremely Slowly

- **Function H :**

$$\begin{cases} H(0)=1 \\ H(i+1)=2^{H(i)} \end{cases}$$

that is: $H(k)=2^{\underbrace{2^2 \dots 2}_{k \text{ 2's}}}$

Note:

H grows extremely fast:

$$H(4)=2^{16}=65536$$

$$H(5)=2^{65536}$$

- **Function Log-star**

$\log^*(j)$ is defined as the least i such that:

$$H(i) \geq j \text{ for } j > 0$$

- **Log-star grows extremely slowly**

$$\lim_{n \rightarrow \infty} \frac{\log^*(n)}{\log^{(p)} n} = 0$$

p is any fixed nonnegative constant

For any x : $2^{16} \leq x \leq 2^{65536} - 1$, $\log^*(x) = 5$!



Grouping Nodes by Ranks

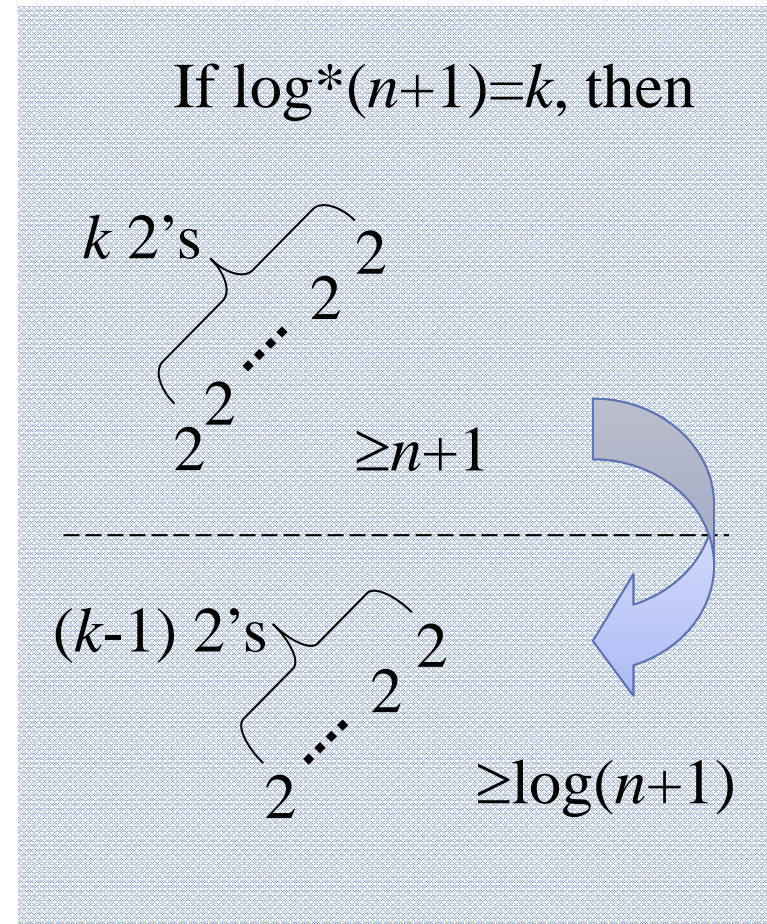
- Node $v \in s_i$ ($i \geq 0$) iff. $\log^*(1 + \text{rank of } v) = i$
 - which means that: if node v is in group i , then
$$r_v \leq H(i) - 1, \text{ but not in group with smaller labels}$$
- So,
 - Group 0: all nodes with rank 0
 - Group 1: all nodes with rank 1
 - Group 2: all nodes with rank 2 or 3
 - Group 3: all nodes with its rank in $[4, 15]$
 - Group 4: all nodes with its rank in $[16, 65535]$
 - Group 5: all nodes with its rank in $[65536, ???]$

Group 5 exists only when n is at least 2^{65536} . What is that?



Very Few Groups

- Node $v \in S_i$ ($i \geq 0$) iff.
 $\log^*(1 + \text{rank of } v) = i$
- Upper bound of the number of distinct node groups is $\log^*(n+1)$
 - The rank of any node in F is at most $\lfloor \log n \rfloor$, so the largest group index is $\log^*(1 + \lfloor \log n \rfloor) = \log^*(\lceil \log n + 1 \rceil) = \log^*(n+1) - 1$



Amortized Cost of *Union-Find*

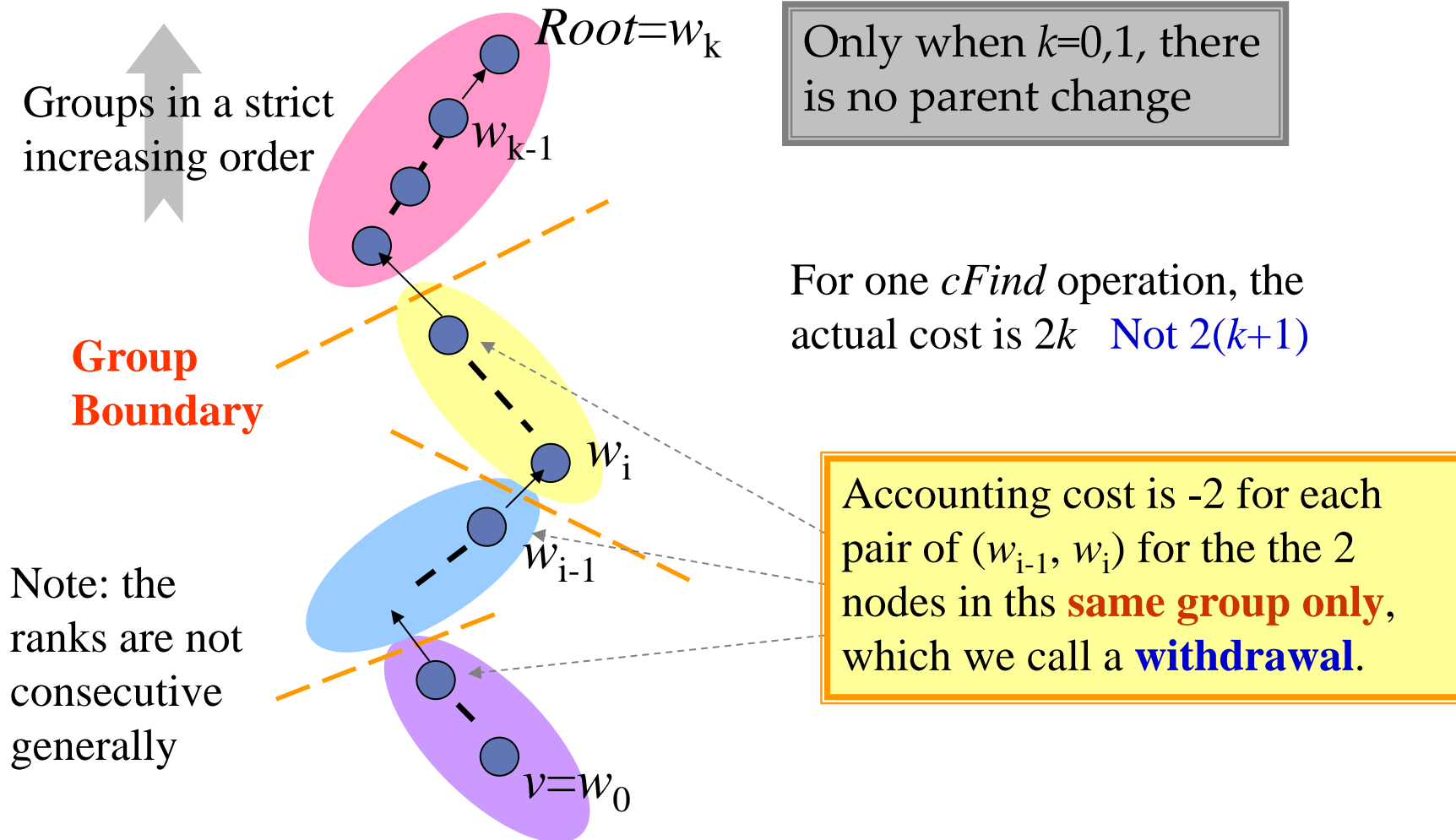
- Amortized Equation Recalled

$$\text{amortized cost} = \text{actual cost} + \text{accounting cost}$$

- The operations to be considered:
 - n makeSets
 - m union & find (with at most $n-1$ unions)



One Execution of $cFind(w_0)$



Amortizing Scheme for *wUnion-cFind*

- **makeSet**
 - Accounting cost is $4\log^*(n+1)$
 - So, the amortized cost is $1+4\log^*(n+1)$
- ***wUnion***
 - Accounting cost is 0
 - So the amortized cost is 1
- ***cFind***
 - Accounting cost is describes as in the previous page.
 - Amortized cost $\leq 2k-2((k-1)-(\log^*(n+1)-1))=2\log^*(n+1)$
(Compare with the worst case cost of *cFind*, $2\log n$)

Number of withdrawal



Validation of the Amortizing Scheme

- We must be assure that **the sum of the accounting costs is never negative.**
- The sum of the negative charges, incurred by *cFind*, does not exceed $4n\log^*(n+1)$
 - We prove this by showing that at most $2n\log^*(n+1)$ withdrawals on nodes occur during all the executions of *cFind*.



Key Idea in the Derivation

- For any node, the number of withdrawal will be less than the number of different ranks in the group it belongs to
 - When a *cFind* changes the parent of a node, the new parent is always has higher rank than the old parent.
 - Once a node is assigned a new parent in a **higher group**, no more negative amortized cost will incurred for it again.
- The number of different ranks is limited within a group.



Derivation

- Bounding the number of withdrawals

The number of withdrawals from all $w \in S$ is:

a loose upper bound
of ranks in a group

$$\sum_{i=0}^{\log^*(n+1)-1} H(i) (\text{number of nodes in group } i)$$

The number of nodes in group i is at most:

$$\sum_{r=H(i-1)}^{H(i)-1} \frac{n}{2^r} \leq \frac{n}{2^{H(i-1)}} \sum_{j=0}^{\infty} \frac{1}{2^j} = \frac{2n}{2^{H(i-1)}} = \frac{2n}{H(i)}$$

So,

$$\sum_{i=0}^{\log^*(n+1)-1} H(i) \frac{2n}{H(i)} = 2n \log^*(n+1)$$



Conclusion

- The number of link operations done by a *Union-Find* program implemented with *wUnion* and *cFind*, of length m on a set of n elements is in $O((n+m)\log^*(n))$ in the worst case.
 - Note: since the sum of accounting cost is never negative, the actual cost is always not less than amortized cost. The upper bound of amortized cost is: $(n+m)(1+4\log^*(n+1))$



Thank you!

Q & A

Yu Huang

<http://cs.nju.edu.cn/yuhuang>

