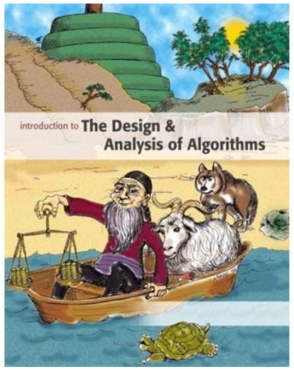
Introduction to

Algorithm Design and Analysis

[10] Union-Find



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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

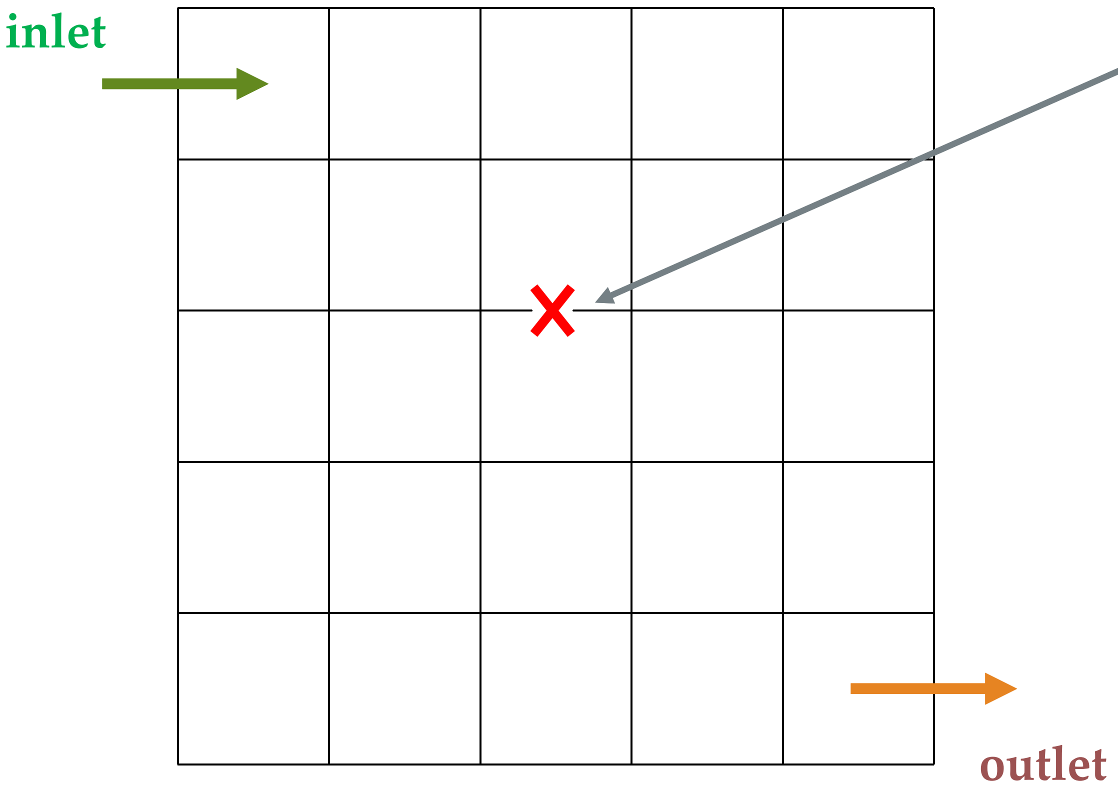
- **Kruskal's algorithm, greedy strategy:**
  - Select one edge
    - With the minimum weight
    - Not in the tree
  - Evaluate this edge
    - This edge will **NOT** result in a cycle
- **Critical issue:**
  - How to know "NO CYCLE"?

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



Select a wall to pull down randomly

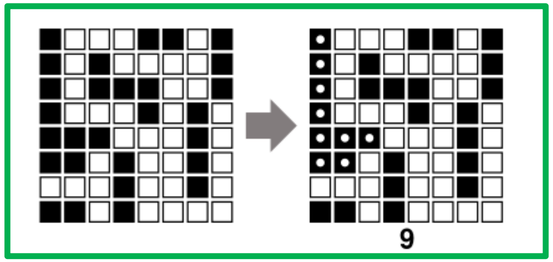
If i and j are in same *equivalence class*, then select another wall to pull down.

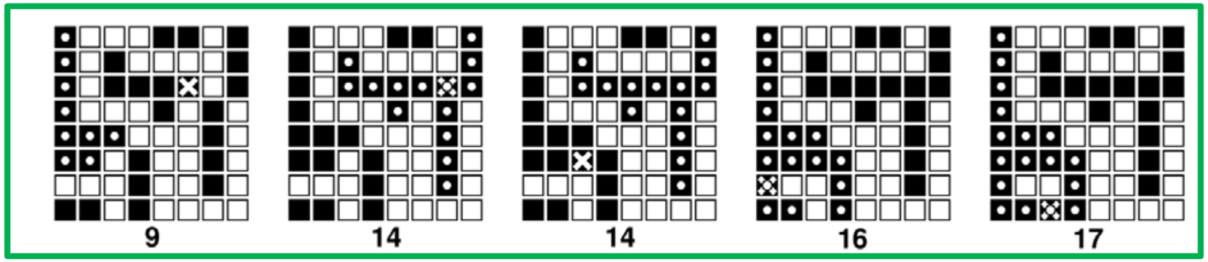
Otherwise, joint the two classes into one.

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

Black Pixels

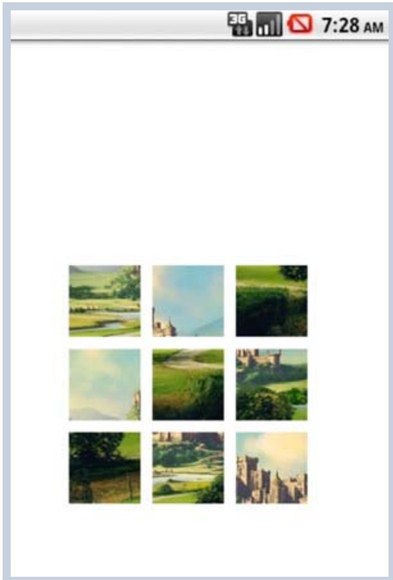
- **Maximum black pixel component**
  - Let α be the size of the component
- **Color one pixel black**
  - How α changes?
  - How to choose the pixel, to accelerate the change in α

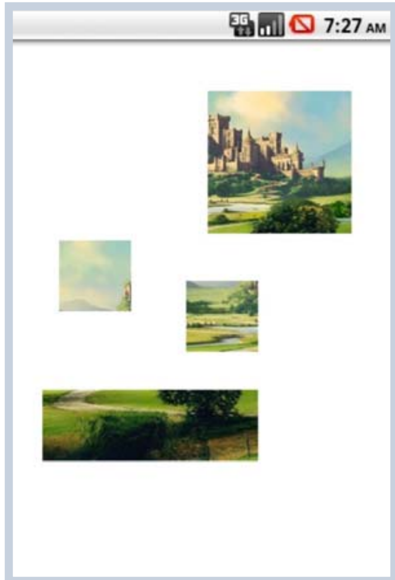




Jigsaw Puzzle

- **Multiple pieces may be glued together**
- **From "one player" to "two players"**
  - o Each group can only be moved in a mutual exclusive way
  - o 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≡4? No
  - 2. **IS** 3≡5? No
  - 3. **MAKE** 3≡5. {{1}, {2}, {3,5}, {4}}
  - 4. **MAKE** 2≡5. {{1}, {2,3,5}, {4}}
  - 5. **IS** 2≡3? Yes
  - 6. **MAKE** 4≡1. {{1,4}, {2,3,5}}
  - 7. **IS** 2≡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 $\Omega(mn)$ (mainly for row copying for MAKE)
- **Array (for equivalence class ID)**
  - Space in $\Theta(n)$, and worst-case cost in $\Omega(mn)$ (mainly for search and change for MAKE)
- **Disjoint Set**
  - A collection of disjoint sets, supporting *Union* and *Find* operations
  - Not necessary to traverse all the elements in one set

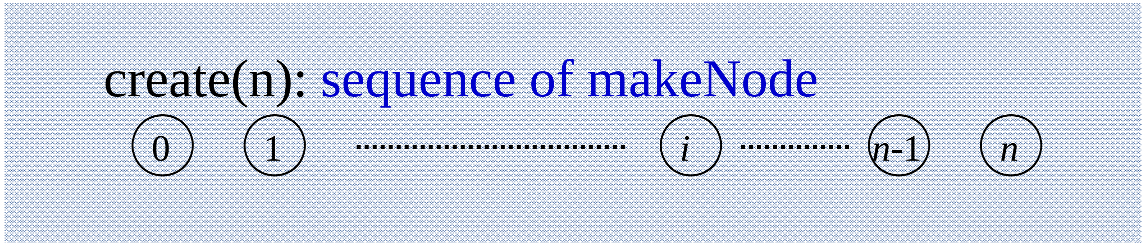
Union-Find ADT

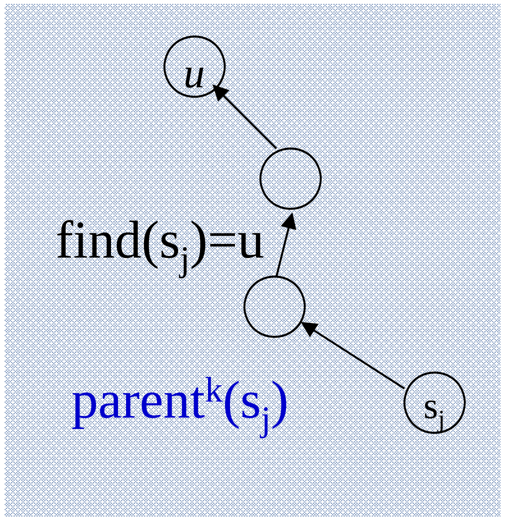
- **Constructor: Union-Find** create(int n)
  - sets=create(n) refers to a newly created group of sets $\{1\}, \{2\}, \ldots, \{n\}$ (n singletons)
- **Access Function: int** find(UnionFind sets, e)
  - find(sets, e)=$\langle e \rangle$
- **Manipulation Procedures**
  - **void** makeSet(UnionFind sets,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

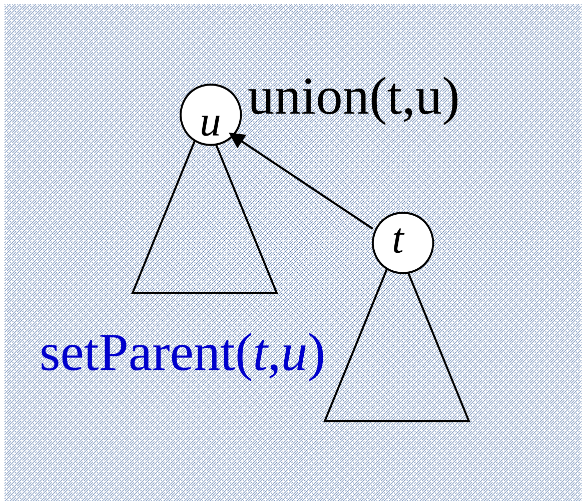
Using Union-Find (as inTree)

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

implementation by inTree







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

Find(1) needs n array lookups

operations done:

$\boldsymbol{n+(n-1)+(m-n+1)n}$ $\quad\boldsymbol{\Theta(mn)}$

Weighted Union: for Short Trees

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

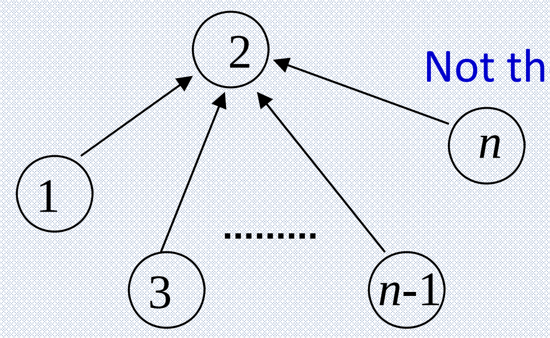
To keep the *Union* valid, each *Union* operation is replaced by:

t=find(i);

u=find(j);

union(t,u)

The order of (t,u) satisfying the requirement



Tree made by wUnion

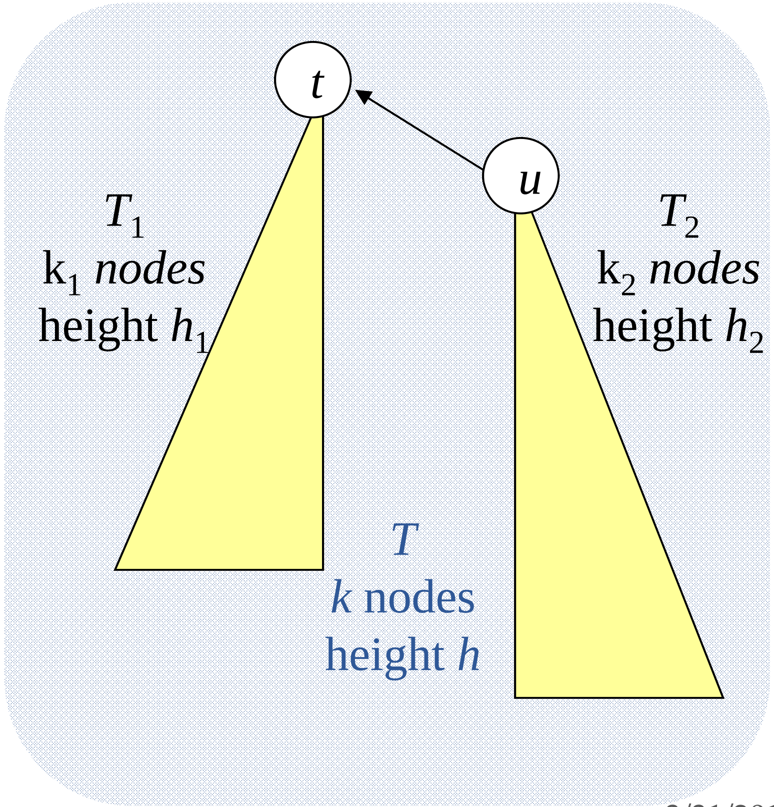
Not the worst case!

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 $\lfloor \log k \rfloor$**
- **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(h1, h2+1), k=k1+k2
    - 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, $h_2+1 \leq \lfloor \lg k_2 \rfloor + 1 \leq \lfloor \lg k \rfloor$

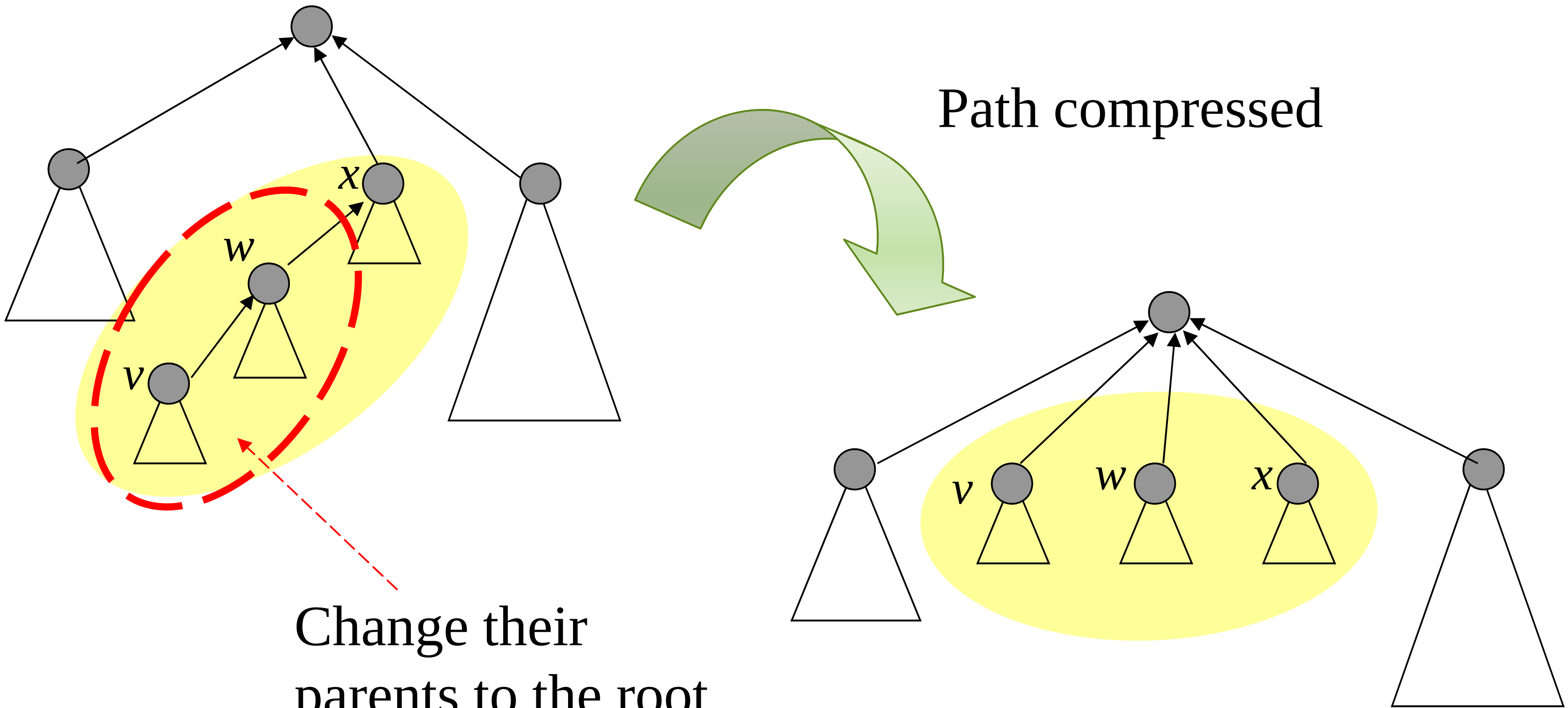


Upper Bound for Union-Find Program

- **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 $m(\lfloor \log n \rfloor + 1) \in O(n+m\log n)$

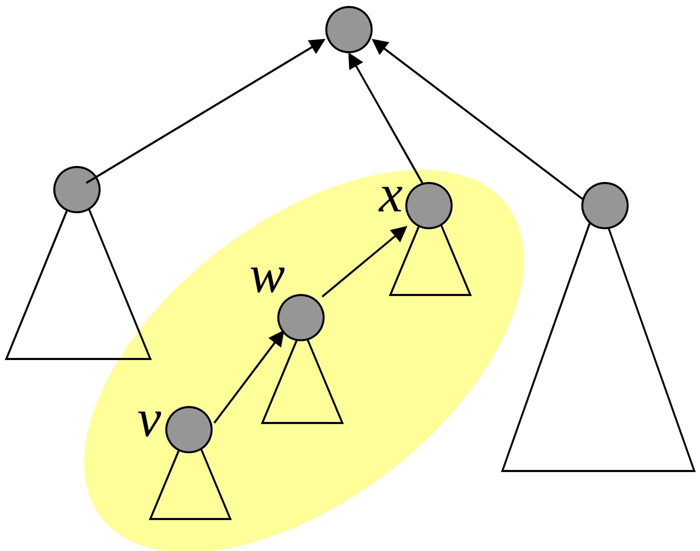
There do exist programs requiring Ω(n+(m-n)logn) steps.

Path Compression

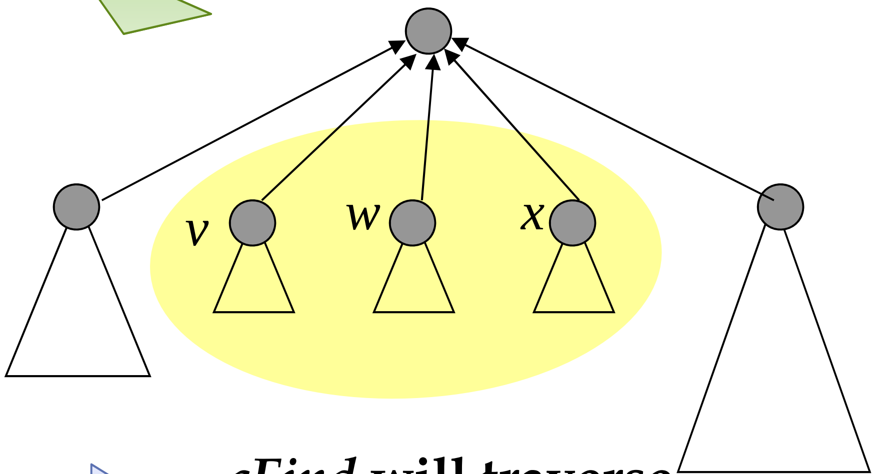


Change their
parents to the root

Challenges for the Analysis



Path compressed



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

but…

cFind **will traverse shorter paths**

Analysis: the Basic Idea

- ***c*Find may be an expensive operation**
  - in the case that find(i) is executed and the node i has great depth.
- **However, such *c*Find 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:

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

- 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:**
  - o *wUnion* is used;
  - o 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*≥0) is** $\dfrac{n}{2^r}$
  - 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 $\lfloor \log n \rfloor$ 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: $H(k)=\underbrace{2^{2^{\cdot^{\cdot^{2}}}}}_{k\ 2\text{'s}}$

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:

$H(i)\geq j$ for $j>0$

- **Log-star grows extremely slowly**

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

***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 $r_v \leq H(i)-1$, 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 $\log^*(1+\lfloor \log n \rfloor)=\log^*(\lceil \log n+1 \rceil) = \log^*(n+1)-1$

If $\log^*(n+1)=k$, then

$$\underbrace{2^{2^{\cdot^{\cdot^{\cdot^{2^{2}}}}}}}_{k\ 2\text{'s}} \geq n+1$$

$$\underbrace{2^{\cdot^{\cdot^{\cdot^{2^{2}}}}}}_{(k-1)\ 2\text{'s}} \geq \log(n+1)$$

Amortized Cost of *Union-Find*

- **Amortized Equation Recalled**

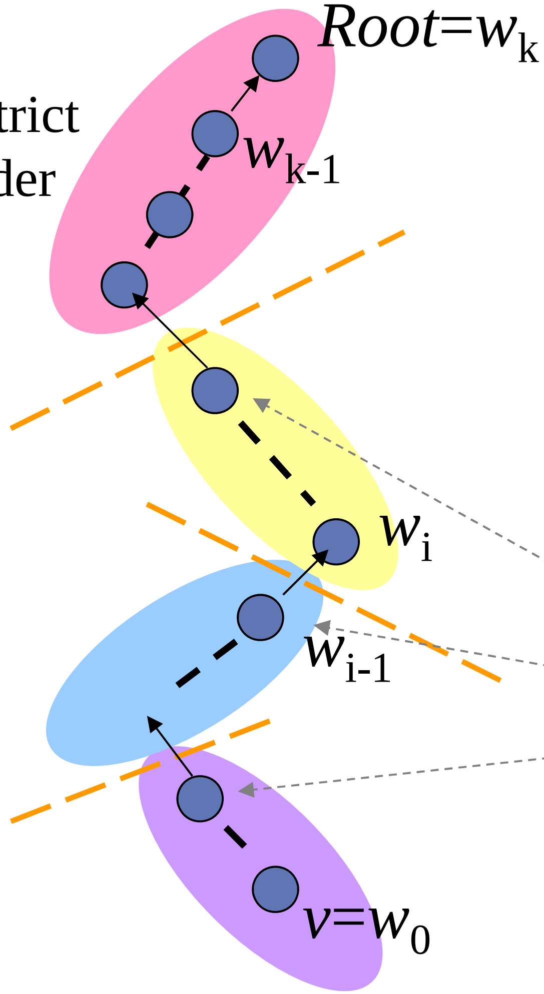
$$\boxed{\text{amortized cost} = \text{actual cost} + \text{accounting cost}}$$

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

One Execution of *cFind*(w_0)

Groups in a strict increasing order

Group Boundary



Note: the ranks are not consecutive generally

Only when k=0,1, there is no parent change

For one *cFind* operation, the actual cost is $2k$ Not $2(k+1)$

Accounting cost is -2 for each pair of (w_{i-1}, w_i) for the the 2 nodes in ths **same group only**, which we call a **withdrawal**.

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 $\leq 2k-2(\underbrace{(k-1)-(\log^*(n+1)-1)}_{\text{Number of withdrawal}})=2\log^*(n+1)$ (Compare with the worst case cost of *cFind*, $2\log n$)

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 *c*Find.

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

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