CSE373: Data Structures & Algorithms
Lecture 10: Implementing Union-Find

Dan Grossman
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The plan

Last lecture:

- What are *disjoint sets*
  – And how are they "the same thing" as *equivalence relations*
- The union-find ADT for disjoint sets
- Applications of union-find

Now:

- Basic implementation of the ADT with "up trees"
- Optimizations that make the implementation much faster

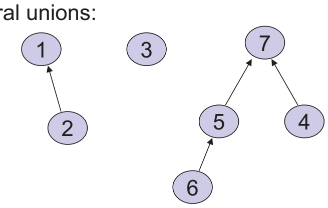
Our goal

- Start with an initial partition of *n* subsets
  – Often 1-element sets, e.g., {1}, {2}, {3}, …, {*n*}
- May have *m* **`find`** operations and up to *n*-1 **`union`** operations in any order
  – After *n*-1 **`union`** operations, every **`find`** returns same 1 set
- If total for all these operations is *O*(*m*+*n*), then amortized *O*(1)
  – We will get very, very close to this
  – *O*(1) worst-case is impossible for **`find`** *and* **`union`**
    • Trivial for one *or* the other

Up-tree data structure

- Tree with:
  – No limit on branching factor
  – References from children to parent
- Start with *forest* of 1-node trees

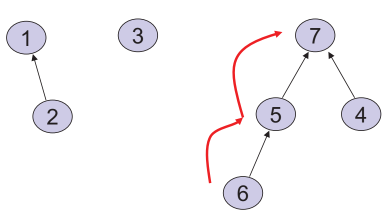
- Possible forest after several unions:
  – Will use roots for set names



Find

`find(x)`:
  – *Assume* we have *O*(1) access to each node
    • Will use an array where index **`i`** holds node **`i`**
  – Start at **`x`** and follow parent pointers to root
  – Return the root

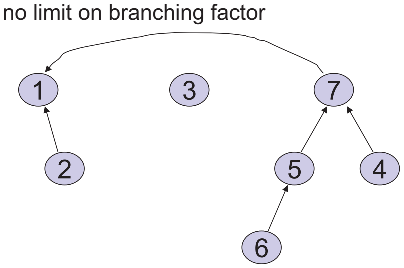
`find`(6) = 7



Union

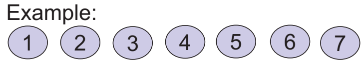
`union(x,y)`:
  – Assume **`x`** and **`y`** are roots
    • Else find the roots of their trees
  – Assume distinct trees (else do nothing)
  – Change root of one to have parent be the root of the other
    • Notice no limit on branching factor

`union`(1,7)



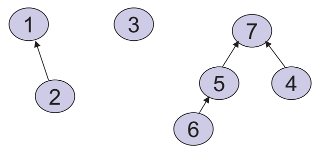
Simple implementation

- If set elements are contiguous numbers (e.g., 1,2,…,*n*), use an array of length *n* called **`up`**
  - Starting at index 1 on slides
  - Put in array index of parent, with 0 (or -1, etc.) for a root
- Example:



	1	2	3	4	5	6	7
up	0	0	0	0	0	0	0

- Example:



	1	2	3	4	5	6	7
up	0	1	0	7	7	5	0

- If set elements are not contiguous numbers, could have a separate dictionary to map elements (keys) to numbers (values)

Implement operations

```
// assumes x in range 1,n
int find(int x) {
  while(up[x] != 0) {
     x = up[x];
  }
  return x;
}
```

```
// assumes x,y are roots
void union(int x, int y){
  up[y] = x;
}
```

- Worst-case run-time for **`union`**?
- Worst-case run-time for **`find`**?
- Worst-case run-time for *m* **`find`**s and *n*-1 **`union`**s?

Implement operations

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// assumes x in range 1,n
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// assumes x,y are roots
void union(int x, int y){
  up[y] = x;
}
```

- Worst-case run-time for **`union`**? $O(1)$
- Worst-case run-time for **`find`**? $O(n)$
- Worst-case run-time for *m* **`find`**s and *n*-1 **`union`**s? $O(n*m)$

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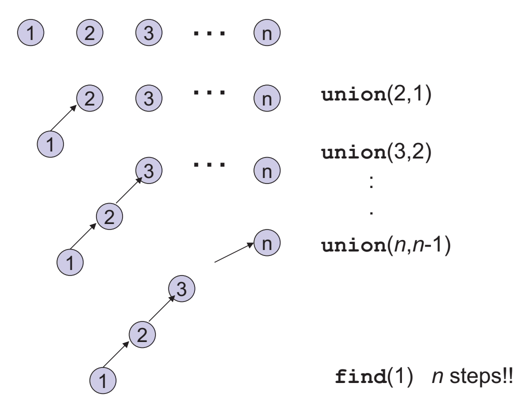
Now:

- Basic implementation of the ADT with "up trees"
- Optimizations that make the implementation much faster

Two key optimizations

1. Improve **`union`** so it stays *O(1)* but makes **`find`** $O(\log n)$
   - So *m* **`find`**s and *n*-1 **`union`**s is $O(m \log n + n)$
   - *Union-by-size:* connect smaller tree to larger tree
2. Improve **`find`** so it becomes even faster
   - Make *m* **`find`**s and *n*-1 **`union`**s ***almost*** $O(m + n)$
   - *Path-compression:* connect directly to root during finds

The bad case to avoid

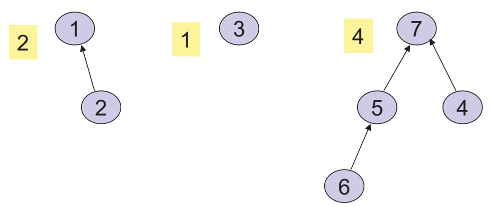


Weighted union

Weighted union:

– Always point the *smaller* (total # of nodes) tree to the root of the larger tree

`union`(1,7)



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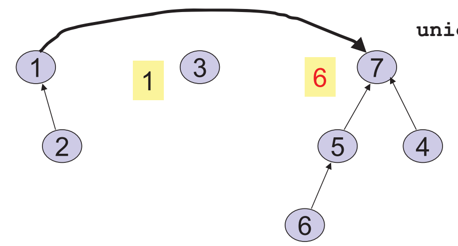
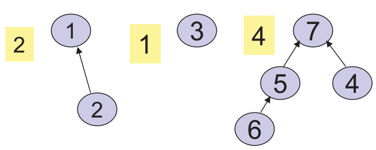


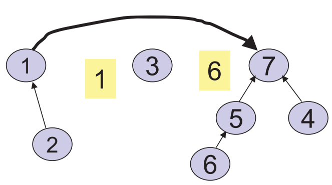
Array implementation

Keep the weight (number of nodes in a second array)

– Or have one array of objects with two fields



	1	2	3	4	5	6	7
up	0	1	0	7	7	5	0
weight	2		1				4



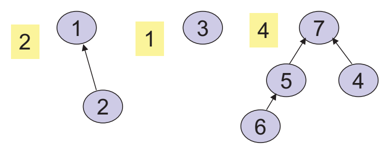
up	7	1	0	7	7	5	0
weight	2		1				6

Nifty trick

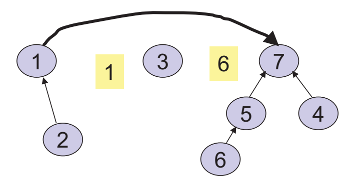
Actually we do not need a second array…

– Instead of storing 0 for a root, store negation of weight

– So up value < 0 means a root

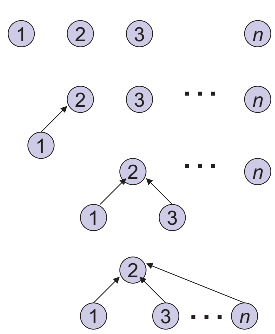


	1	2	3	4	5	6	7
up	-2	1	-1	7	7	5	-4



up	7	1	-1	7	7	5	-6

Bad example? Great example…



`union`(2,1)

`union`(3,2)

:

`union`(n,n-1)

`find`(1) *constant here*

General analysis

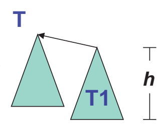
- Showing one worst-case example is now good is *not* a proof that the worst-case has improved
- So let's prove:
  - `union` is still $O(1)$ – this is "obvious"
  - `find` is now $O(\log n)$
- Claim: If we use weighted-union, an up-tree of height h has at least 2^h nodes
  - Proof by induction on h…

Exponential number of nodes

P(h)= With weighted-union, up-tree of height h has at least 2^h nodes

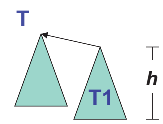
Proof by induction on h…

- Base case: h = 0: The up-tree has 1 node and 2^0= 1
- Inductive case: Assume P(h) and show P(h+1)
  - A height h+1 tree T has at least one height h child T1
  - T1 has at least 2^h nodes by induction
  - And T has *at least* as many nodes not in T1 than in T1
    - Else weighted-union would have had T point to T1, not T1 point to T (!!)
  - So total number of nodes is *at least* $2^h + 2^h = 2^{h+1}$



The key idea

Intuition behind the proof: No one child can have more than half the nodes

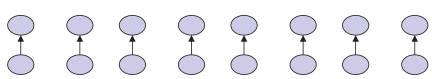


So, as usual, if number of nodes is exponential in height, then height is logarithmic in number of nodes

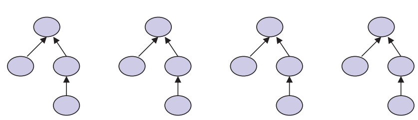
So **`find`** is O(**`log`** n)

The new worst case

n/2 Weighted Unions

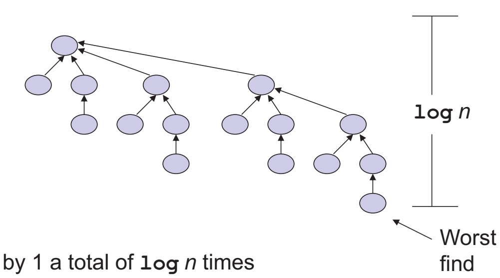


n/4 Weighted Unions



The new worst case (continued)

After n/2 + n/4 + …+ 1 Weighted Unions:



Height grows by 1 a total of **`log`** n times

What about union-by-height

We could store the height of each root rather than number of descendants (weight)

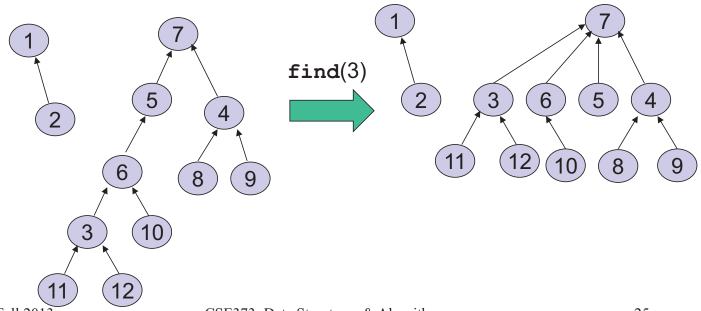
- Still guarantees logarithmic worst-case find
  - Proof left as an exercise if interested
- But does not work well with our next optimization
  - Maintaining height becomes inefficient, but maintaining weight still easy

Two key optimizations

1. Improve **`union`** so it stays *O(1)* but makes **`find`** O(**`log`** n)
   - So m **`find`**s and n-1 **`union`**s is O(m **`log`** $n + n$)
   - *Union-by-size:* connect smaller tree to larger tree
2. Improve **`find`** so it becomes even faster
   - Make m **`find`**s and n-1 **`unions`** ***almost*** $O(m + n)$
   - *Path-compression:* connect directly to root during finds

Path compression

- Simple idea: As part of a **`find`**, change each encountered node's parent to point directly to root
  - Faster future **`find`**s for everything on the path (and their descendants)



Pseudocode

```
// performs path compression
int find(i) {
  // find root
  int r = i
  while(up[r] > 0)
     r = up[r]
  // compress path
  if i==r
    return r;
  int old_parent = up[i]
  while(old_parent != r) {
    up[i] = r
    i = old_parent;
    old_parent = up[i]
  }
  return r;
}
```


So, how fast is it?

A single worst-case **`find`** could be $O($**`log`** $n)$
- But only if we did a lot of worst-case unions beforehand
- And path compression will make future finds faster

Turns out the amortized worst-case bound is much better than $O($**`log`** $n)$
- We won't *prove* it – see text if curious
- But we will *understand* it:
  - How it is *almost* $O(1)$
  - Because total for m **`find`**s and n-1 **`union`**s is *almost* $O(m+n)$

A really slow-growing function

`log*` x is the minimum number of times you need to apply "**`log`** of **`log`** of **`log`** of" to go from x to a number <= 1

For just about every number we care about, **`log*`** x is *5* (!)
If $x \le 2^{65536}$ then **`log*`** x <= 5
- log* 2 = 1
- log* 4 = log* 2^2 = 2
- log* 16 = log* $2^{(2^2)}$ = 3 (log log log 16 = 1)
- log* 65536 = log* $2^{((2^2)^2)}$ = 4 (log log log log 65536 = 1)
- log* 2^{65536} = …………… = 5

Almost linear

- Turns out total time for m **`find`**s and n-1 **`union`**s is $O((m+n)$*(**`log*`** $(m+n))$
  - Remember, if $m+n < 2^{65536}$ then **`log*`** $(m+n) < 5$
- At this point, it feels almost silly to mention it, but even that bound is not tight…
  - "Inverse Ackerman's function" grows even more slowly than **`log*`**
    - Inverse because Ackerman's function grows really fast
    - Function also appears in combinatorics and geometry
    - For any number you can possibly imagine, it is < 4
  - Can replace **`log*`** with "Inverse Ackerman's" in bound

Theory and terminology

- Because **`log*`** or Inverse Ackerman's grows soooo slowly
  - For all practical purposes, amortized bound is constant, i.e., total cost is linear
  - We say "near linear" or "effectively linear"
- Need weighted-union and path-compression for this bound
  - Path-compression changes height but not weight, so they interact well
- As always, asymptotic analysis is separate from "coding it up"