Announcements

• Homework 3 due in ONE week…Wednesday April 30th!

• TA sessions
  – Thursday: Disjoint sets and union-find ADT
  – Next Tuesday: Extra help with homework 3

• Nicki away next week on Monday and Wednesday
  – Aaron Bauer will teach you about hashing
The plan

Last lecture:

• Disjoint sets
• The union-find ADT for disjoint sets

Today’s lecture:

• Basic implementation of the union-find ADT with “up trees”
• Optimizations that make the implementation much faster
Union-Find ADT

• Given an unchanging set $S$, \textit{create} an initial partition of a set
  – Typically each item in its own subset: \{a\}, \{b\}, \{c\}, …
  – Give each subset a “name” by choosing a \textit{representative element}

• Operation \textit{find} takes an element of $S$ and returns the representative element of the subset it is in

• Operation \textit{union} takes two subsets and (permanently) makes one larger subset
  – A different partition with one fewer set
  – Affects result of subsequent \textit{find} operations
  – Choice of representative element up to implementation
Implementation – our goal

• Start with an initial partition of \( n \) subsets
  – Often 1-element sets, e.g., \{1\}, \{2\}, \{3\}, …, \{n\}

• May have \( m \) \texttt{find} operations

• May have up to \( n-1 \) \texttt{union} operations in any order
  – After \( n-1 \) \texttt{union} operations, every \texttt{find} returns same 1 set
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

\textbf{find}(x):

- \textit{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

\texttt{find}(6) = 7
**Union**

\( \text{union}(x,y) : \)
- 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

\( \text{union}(1,7) \)
Simple implementation

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

- Example:

- Example:

- 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? \( O(1) \)
• Worst-case run-time for find? \( O(n) \)
• Worst-case run-time for \( m \) finds and \( n-1 \) unions? \( O(m*n) \)
Two key optimizations

1. Improve union so it stays $O(1)$ but makes find $O(\log n)$
   - So $m$ finds and $n-1$ unions is $O(m \log n + n)$
   - Union-by-size: connect smaller tree to larger tree

2. Improve find so it becomes even faster
   - Make $m$ finds and $n-1$ unions almost $O(m + n)$
   - Path-compression: connect directly to root during finds
The bad case to avoid

\[ 1 \quad 2 \quad 3 \quad \ldots \quad n \]

union(2,1)

union(3,2)

\vdots

union(n,n-1)

\[ \text{find}(1) = n \text{ steps!!} \]
Union-by-size

Union-by-size:
- Always point the smaller (total # of nodes) tree to the root of the larger tree

```
union(1,7)
```
Union-by-size

Union-by-size:

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

```
  union(1,7)
  /   \
 1    7
  |    |
 2    6
  |    |
 3    5
  |    |
 4
```
Array implementation

Keep the size (number of nodes in a second array)
- Or have one array of objects with two fields
**Nifty trick**

Actually we do not need a second array…

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

– So up value < 0 means a root
The Bad case? Now a Great case...

union(2,1)

union(3,2)

union(n,n-1)

find(1) \textit{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 union-by-size, an up-tree of height $h$ has at least $2^h$ nodes
  – Proof by induction on $h$…
Exponential number of nodes

P(h)= With union-by-size, 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 union-by-size 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 Unions-by-size

n/4 Unions-by-size
The new worst case (continued)

After \( n/2 + n/4 + \ldots + 1 \) Unions-by-size:

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 size

- 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 size still easy
Two key optimizations

1. Improve `union` so it stays $O(1)$ but makes `find` $O(\log n)$
   - So $m$ finds and $n-1$ unions is $O(m \log n + n)$
   - *Union-by-size*: connect smaller tree to larger tree

2. Improve `find` so it becomes even faster
   - Make $m$ finds 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 finds for everything on the path (and their descendants)
// 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 $m$ finds and $n-1$ unions 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 $\leq 1$

For just about every number we care about, $log^* x$ is 5 (!)

If $x \leq 2^{65536}$ then $log^* x \leq 5$

- $log^* 2 = 1$
- $log^* 4 = log^* 2^2 = 2$
- $log^* 16 = log^* 2^{(2^2)} = 3$ (log log log 16 = 1)
- $log^* 65536 = log^* 2^{((2^2)^2)} = 4$ (log log log log 65536 = 1)
- $log^* 2^{65536} = \ldots \ldots = 5$
Almost linear

- Turns out total time for $m$ finds and $n-1$ unions is $O((m+n)^*(\log^* (m+n)))$
  - Remember, if $m+n < 2^{65536}$ then $\log^* (m+n) < 5$
    so effectively we have $O(m+n)$
- Because $\log^*$ grows soooo slowly
  - For all practical purposes, amortized bound is constant, i.e.,
    cost of find is constant, total cost for $m$ finds is linear
  - We say “near linear” or “effectively linear”
- Need union-by-size 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”