Disjoint Union / Find

CSE 373

Data Structures

Unit 14

Reading: Chapter 8

Equivalence Relations

- A relation R is defined on set S if for every pair of elements a, b$\in$S, a R b is either true or false.
- An equivalence relation is a relation R that satisfies the 3 properties:
  - Reflexive: a R a for all a$\in$S
  - Symmetric: a R b iff b R a; for all a,b$\in$S
  - Transitive: a R b and b R c implies a R c

Equivalence Classes

- Given an equivalence relation R, decide whether a pair of elements a,b$\in$S is such that a R b.
- The equivalence class of an element a is the subset of S of all elements related to a.
- Equivalence classes are disjoint sets

Dynamic Equivalence Problem

- Starting with each element in a singleton set, and an equivalence relation, build the equivalence classes
- Requires two operations:
  - Find the equivalence class (set) of a given element
  - Union of two sets
- It is a dynamic (on-line) problem because the sets change during the operations and Find must be able to cope!

Disjoint Union - Find

- Maintain a set of disjoint sets.
  - › {3,5,7} , {4,2,8}, {9}, {1,6}
- Each set has a unique name, one of its members
  - › $\{3,\underline{5},7\}$, $\{4,2,\underline{8}\}$, $\{\underline{9}\}$, $\{\underline{1},6\}$

Union

- Union(x,y) – take the union of two sets named x and y
  - › $\{3,\underline{5},7\}$, $\{4,2,\underline{8}\}$, $\{\underline{9}\}$, $\{\underline{1},6\}$
  - › Union(5,1)

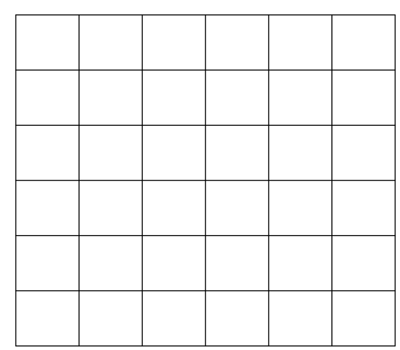
    $\{3,\underline{5},7,1,6\}$, $\{4,2,\underline{8}\}$, $\{\underline{9}\}$,

Find

- Find(x) – return the name of the set containing x.
  - › $\{3,\underline{5},7,1,6\}$, $\{4,2,\underline{8}\}$, $\{\underline{9}\}$,
  - › Find(1) = 5
  - › Find(4) = 8

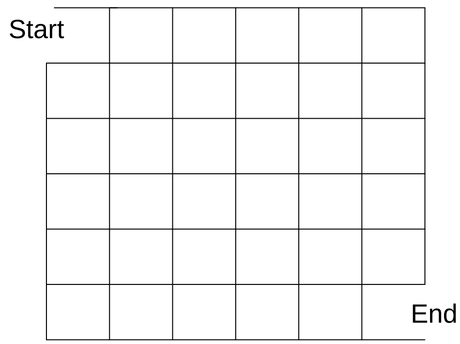
An Application

- Build a random maze by erasing edges.



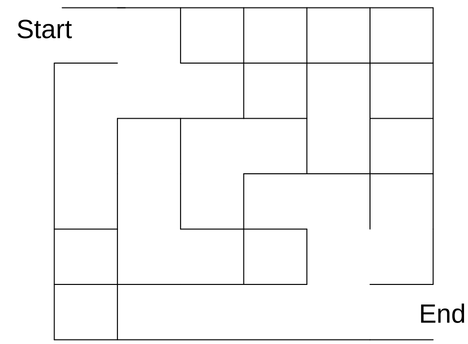
An Application (ct'd)

- Pick Start and End



An Application (ct'd)

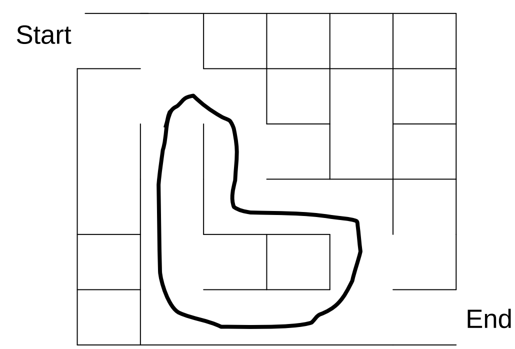
- Repeatedly pick random edges to delete.



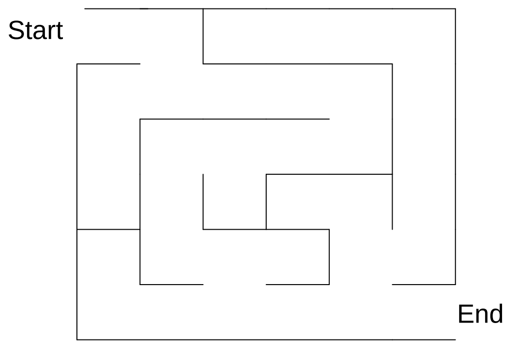
Desired Properties

- None of the boundary is deleted
- Every cell is reachable from every other cell.
- There are no cycles – no cell can reach itself by a path unless it retraces some part of the path.

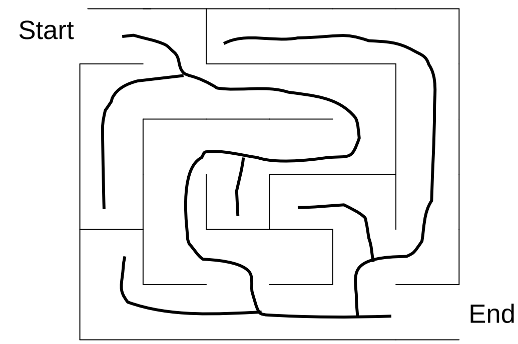
A Cycle (we don't want that)



A Good Solution



Good Solution : A Hidden Tree



Number the Cells

We have disjoint sets S ={ {1}, {2}, {3}, {4},… {36} } each cell is unto itself.
We have all possible edges E ={ (1,2), (1,7), (2,8), (2,3), … } 60 edges total.

Start

1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

End

Basic Algorithm

- S = set of sets of connected cells
- E = set of edges

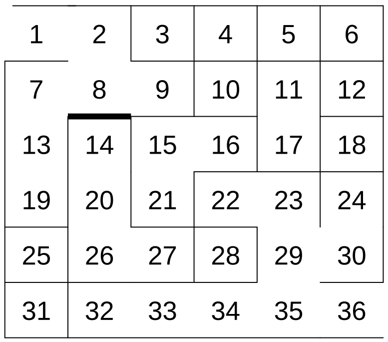
```
While there is more than one set in S
   pick a random edge (x,y)
   u := Find(x);  v := Find(y);
   if u ≠ v then
        Union(u,v)  //knock down the wall between the cells (cells in
.       Remove (x,y) from E         //the same set are connected)
```

- If u=v there is already a path between x and y
- All remaining members of E form the maze

Example Step

Pick (8,14)

Start



End

S
{1,2,7,8,9,13,19}
{3}
{4}
{5}
{6}
{10}
{11,17}
{12}
{14,20,26,27}
{15,16,21}
.
.
{22,23,24,29,30,32
33,34,35,36}

Example

S
{1,2,7,8,9,13,19}
{3}
{4}
{5}
{6}
{10}
{11,17}
{12}
{14,20,26,27}
{15,16,21}
.
.
{22,23,24,29,39,32
33,34,35,36}

Find(8) = 7
Find(14) = 20

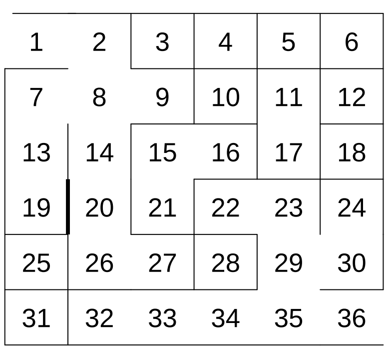
Union(7,20)

S
{1,2,7,8,9,13,19,14,20 26,27}
{3}
{4}
{5}
{6}
{10}
{11,17}
{12}
{15,16,21}
.
.
{22,23,24,29,39,32
33,34,35,36}

Example

Pick (19,20)

Start

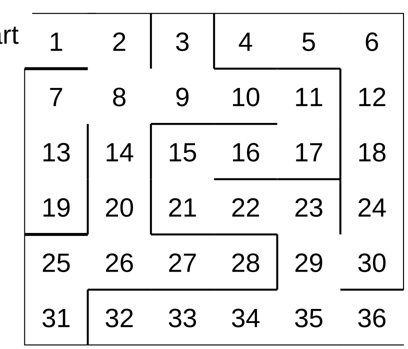


End

S
{1,2,7,8,9,13,19
14,20,26,27}
{3}
{4}
{5}
{6}
{10}
{11,17}
{12}
{15,16,21}
.
.
{22,23,24,29,39,32
33,34,35,36}

Example at the End

Start



End

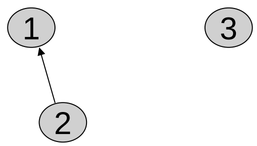
S
{1,2,3,4,5,6,7,… 36}

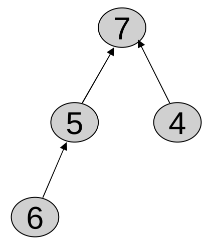
E

Up-Tree for DU/F

Initial state

Intermediate state

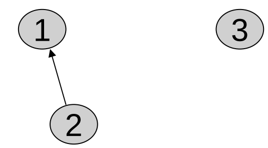


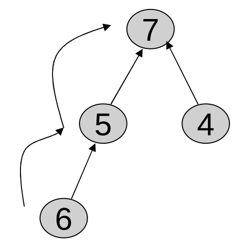


Roots are the names of each set.

Find Operation

- Find(x) follow x to the root and return the root



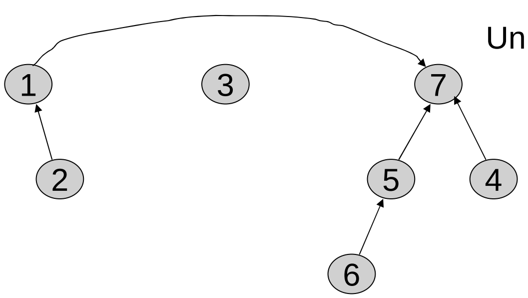


Find(6) = 7

Union Operation

- Union(i,j) - assuming i and j roots, point i to j.

Union(1,7)

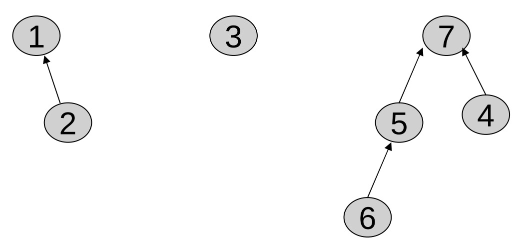


Simple Implementation

- Array of indices (Up[i] is parent of i)

Up [x] = 0 means x is a root.

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



Union

```
Union(up[] : integer array, x,y : integer) : {
//precondition: x and y are roots//
Up[x] := y
}
```

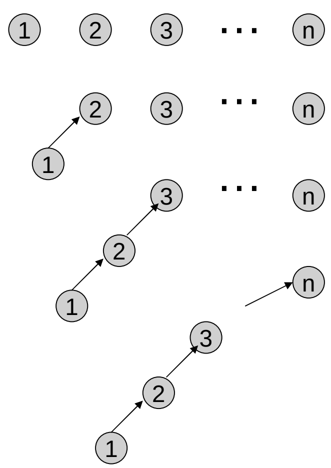
Constant Time!

Find

- Design Find operator
  - › Recursive version
  - › Iterative version

```
Find(up[] : integer array, x : integer) : integer {
//precondition: x is in the range 1 to size//
???
}
```


A Bad Case



Union(1,2)

Union(2,3)

:

:

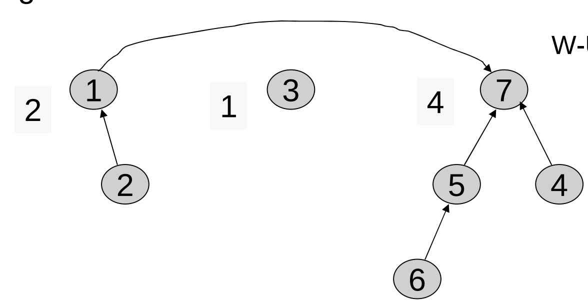
Union(n-1,n)

Find(1) n steps!!

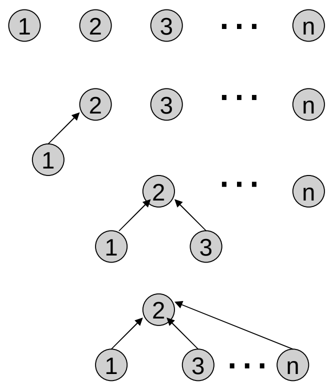
Weighted Union

- Weighted Union (weight = number of nodes)
  - › Always point the smaller tree to the root of the larger tree

W-Union(1,7)



Example Again



Union(1,2)

Union(2,3)

:

:

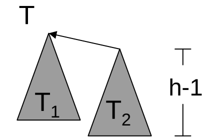
Union(n-1,n)

Find(1) constant time

Analysis of Weighted Union

- With weighted union an up-tree of height h has weight at least 2^h.
- Proof by induction
  - › Basis: h = 0. The up-tree has one node, $2^0 = 1$
  - › Inductive step: Assume true for all h' < h.

Minimum weight up-tree of height h formed by weighted unions



$W(T_1) \geq W(T_2) \geq 2^{h-1}$

Weighted union

Induction hypothesis

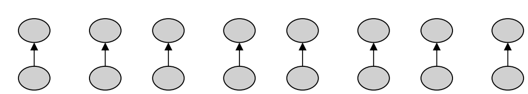
$W(T) \geq 2^{h-1} + 2^{h-1} = 2^h$

Analysis of Weighted Union

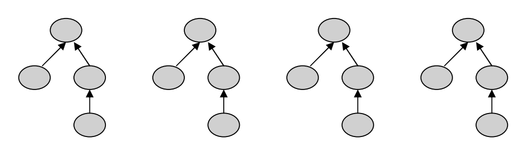
- Let T be an up-tree of weight n formed by weighted union. Let h be its height.
- $n \geq 2^h$
- $\log_2 n \geq h$
- Find(x) in tree T takes O(log n) time.
- Can we do better?

Worst Case for Weighted Union

n/2 Weighted Unions

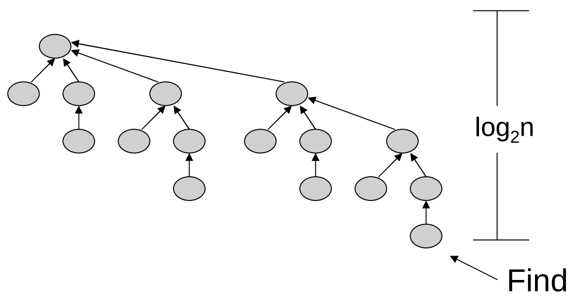


n/4 Weighted Unions



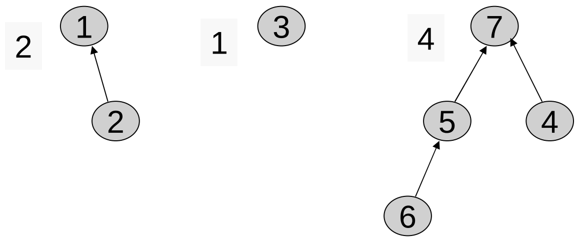
Example of Worst Cast (cont')

After n -1 = n/2 + n/4 + …+ 1 Weighted Unions



If there are $n = 2^k$ nodes then the longest path from leaf to root has length k.

Elegant Array Implementation



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

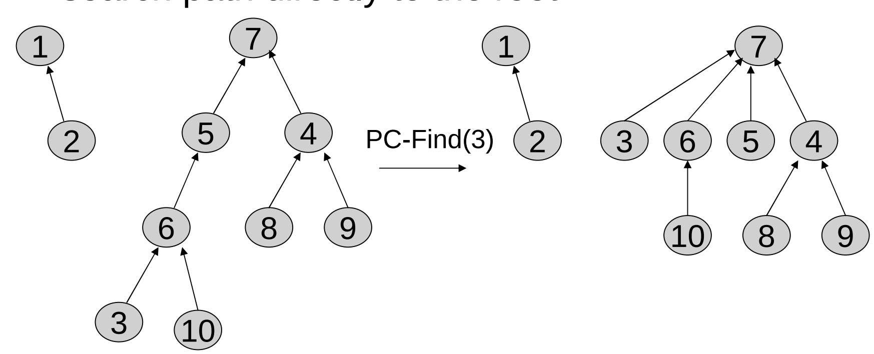
Can save the extra space by storing the complement of weight in the space reserved for the root

Weighted Union

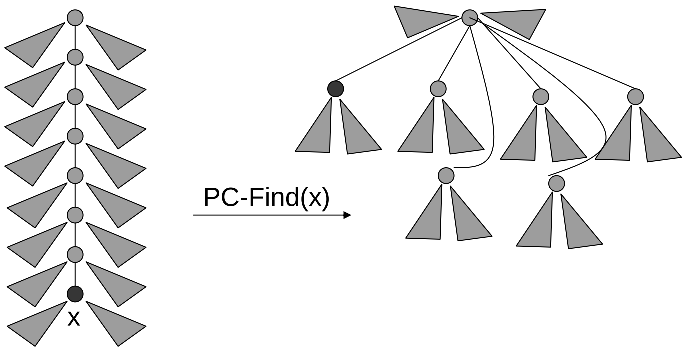
```
W-Union(i,j : index){
//i and j are roots//
  wi := weight[i];
  wj := weight[j];
  if wi < wj then
    up[i] := j;
    weight[j] := wi + wj;
  else
    up[j] :=i;
    weight[i] := wi +wj;
}
```


Path Compression

- On a Find operation point all the nodes on the search path directly to the root.



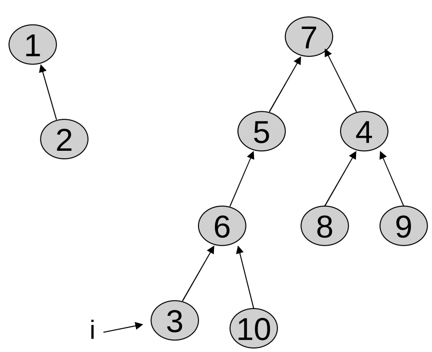
Self-Adjustment Works



Path Compression Find

```
PC-Find(i : index) {
  r := i;
  while up[r] ≠ 0 do //find root//
    r := up[r];
  if i ≠ r then  //compress path//
    k := up[i];
    while k ≠ r do
      up[i] := r;
      i := k;
      k := up[k]
  return(r)
}
```


Example



Disjoint Union / Find with Weighted Union and PC

- Worst case time complexity for a W-Union is O(1) and for a PC-Find is O(log n).
- Time complexity for m ≥ n operations on n elements is O(m log* n) where log* n is a very slow growing function.
  - › log * n < 7 for all reasonable n. Essentially constant time per operation!

Amortized Complexity

- For disjoint union / find with weighted union and path compression.
  - › average time per operation is essentially a constant.
  - › worst case time for a PC-Find is O(log n).
- An individual operation can be costly, but over time the average cost per operation is not.

Find Solutions

Recursive

```
Find(up[] : integer array, x : integer) : integer {
//precondition: x is in the range 1 to size//
if up[x] = 0 then return x
else return Find(up,up[x]);
}
```

Iterative

```
Find(up[] : integer array, x : integer) : integer {
//precondition: x is in the range 1 to size//
while up[x] ≠ 0 do
  x := up[x];
return x;
}
```