Objectives

- Data structures: Heaps, Graphs

Review: Priority Queues for Sorting

1. Add elements into PQ with the number's value as its priority
2. Then extract the smallest number until done
   - Come out in sorted order

Sorting *n* numbers takes at least O(n logn) time

What is the goal running time for our PQ's operations? **O(logn)**

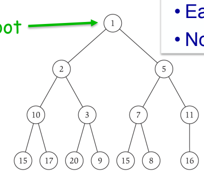
Already know our "loops" will be O(n)

Heap Defined

- Combines benefits of sorted array and list
- Balanced binary tree

- Each node has *at most* 2 children
- Node value is its *key*

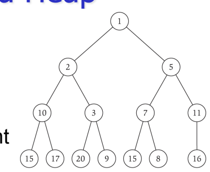
root



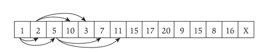
Heap order: each node's key is at least as large as its parent's

Note: **not** a binary search tree

Review: Implementing a Heap



- Option 1: Use pointers
  - Each node keeps
    - Element it stores, key
    - 3 pointers: 2 children, parent
- Option 2: No pointers
  - Requires knowing upper bound on *n*
  - For node at position *i*
    - left child is at *2i*
    - right child is at *2i+1*

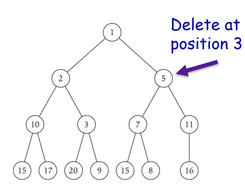


Heapify-Up

- Claim. Assuming array H is almost a heap with key of `H[i]` too small, `Heapify-Up` fixes the heap property in O(log i) time
  - Can insert a new element in a heap of *n* elements in O(log n) time
- Proof. By induction
  - If i=1, is already a heap → O(1)
  - If i>1,
    - Swaps are O(1)
    - Swaps continue up to root (max) → log i

Deleting an Element

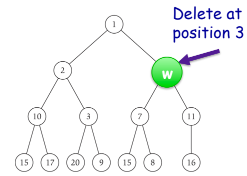
- Delete at position *i*



Deleting an Element

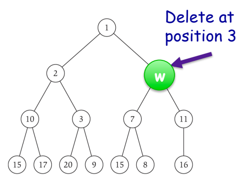
- Delete at position *i*
- Removing an element:
  - Messes up heap order
  - Leaves a “hole” in the heap
- Not as straightforward as `Heapify-Up`
- Algorithm
  1. Fill in element where hole was
     - Patch hole: move n^{th} element into i^{th} spot
  2. Adjust heap to be in order
     - At position *i* because moved n^{th} item up to *i*

Deleting an Element



- What are the possibilities when we move n^{th} element (*w*) into spot where element was removed?
  - Give an example for each possibility

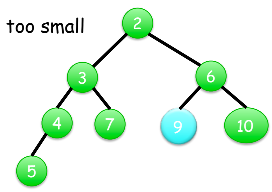
Deleting an Element



- Two possibilities: element *w* is
  - Too small: violation is between it and parent → `Heapify-Up` (example: w = 0)
  - Too big: with one or both children → `Heapify-Down` (example: w = 12)

Deleting an Element

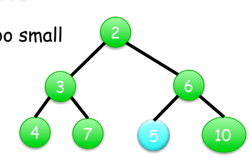
Example where new key is too small



- Delete 9
- Replace with 5

Deleting an Element

Example where new key is too small



- Delete 9
- Replace with 5
- But 5 < 6, so need to `Heapify-Up`

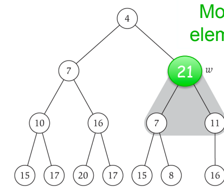
Heapify-Down

```
Heapify-down(H, i):
   n = length(H)
   if 2i > n then          Why can we stop?
      Terminate with H unchanged
   else if 2i < n then
      left=2i and right=2i+1
      j be index that minimizes
            key[H[left]] and key[[H[right]]
   else if 2i = n then
      j=2i

   if key[H[j]] < key[H[i]] then
      swap array entries H[i] and H[j]
      Heapify-down(H, j)
```

Heapify-Down

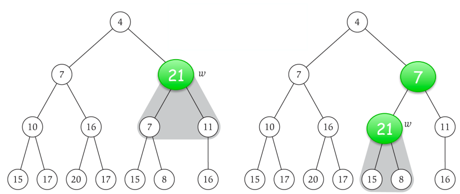
```
Heapify-down(H, i):
   n = length(H)
   if 2i > n then          i is a leaf – nowhere to go
      Terminate with H unchanged
   else if 2i < n then
      left=2i and right=2i+1
      j be index that minimizes
            key[H[left]] and key[[H[right]]
   else if 2i = n then
      j=2i

   if key[H[j]] < key[H[i]] then
      swap array entries H[i] and H[j]
      Heapify-down(H, j)
```


Practice: Heapify-Down

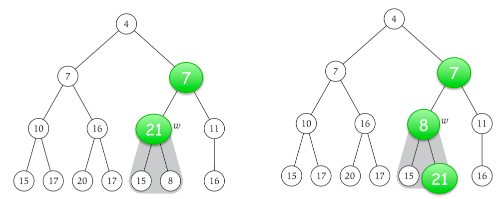


Moved 21 to where element was removed

Practice: Heapify-Down



Practice: Heapify-Down



Runtime of Heapify-Down?

```
Heapify-down(H, i):
   n = length(H)
   if 2i > n then
      Terminate with H unchanged
   else if 2i < n then
      left=2i and right=2i+1
      j be index that minimizes      O(1)
            key[H[left]] and key[[H[right]]
   else if 2i = n then
      j=2i

   if key[H[j]] < key[H[i]] then
      swap array entries H[i] and H[j]  O(1)
      Heapify-down(H, j)
```

Num swaps: $O(\log n)$

Implementing Priority Queues with Heaps

Operation	Description	Run Time
StartHeap(N)	Creates an empty heap that can hold N elements	
Insert(v)	Inserts item v into heap	
FindMin()	Identifies minimum element in heap but does not remove it	
Delete(i)	Deletes element in heap at position i	
ExtractMin()	Identifies and deletes an element with minimum key from heap	

Implementing Priority Queues with Heaps

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Delete(i)	Deletes element in heap at position i	O(log n)
ExtractMin()	Identifies and deletes an element with minimum key from heap	O(log n)

Comparing Data Structures

Operation	Heap	Unsorted List	Sorted List
StartHeap(N)			
Insert(v)			
FindMin()			
Delete(i)			
ExtractMin()			

Comparing Data Structures

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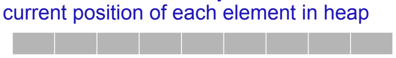
Comparing Data Structures

Operation	Heap	Unsorted List	Sorted List
StartHeap(N)	O(N)	O(1)	O(1)
Insert(v)	O(log n)	O(1)	O(n)
FindMin()	O(1)	O(n)	O(1)
Delete(i)	O(log n)	O(n)	O(n)
ExtractMin()	O(log n)	O(n)	O(1)

Additional Heap Operations

- Access given element of PQ
  - Maintain additional array `Position` that stores current position of each element in heap

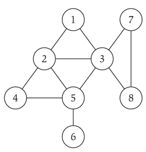


- Operations:
  - Delete(Position[v])
    - Does not increase overall running time
  - ChangeKey(v, α)
    - Changes key of element v to key(v) = α
    - Identify position of element v in array (`Position` array)
    - Change key, heapify

GRAPHS

Undirected Graphs G = (V, E)

- V = nodes (vertices)
- E = edges between pairs of nodes
- Captures pairwise relationship between objects
- Graph size parameters: n = |V|, m = |E|

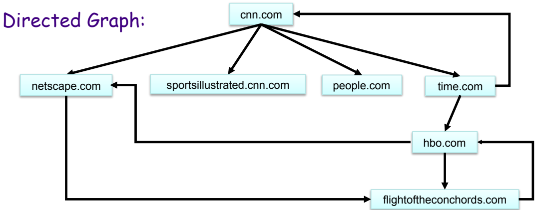


V = { 1, 2, 3, 4, 5, 6, 7, 8 }
E = { 1-2, 1-3, 2-3, 2-4, 2-5, 3-5, 3-7, 3-8, 4-5, 5-6 }
n = 8
m = 11

World Wide Web

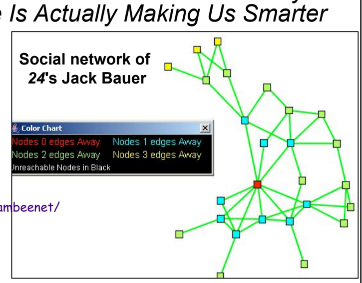
- Web graph
  - Node: web page
  - Edge: hyperlink from one page to another

Directed Graph:



Social Networks

- Node: people; Edge: relationship between 2 people
- *Everything Bad Is Good for You: How Today's Popular Culture Is Actually Making Us Smarter*
  - Television shows have complex plots, complex social networks

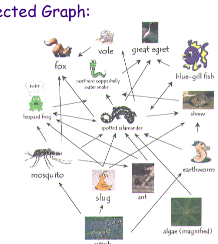


http://www.cs.duke.edu/csed/harambeenet/modules.html

Ecological Food Web

- Food web graph
  - Node = species
  - Edge = from prey to predator

Directed Graph:



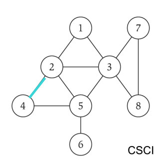
Reference:
http://www.twingroves.district96.k12.il.us/Wetlands/Salamander/SalGraphics/salfoodweb.giff

Graph Applications

Graph	*Nodes*	*Edges*
transportation	street intersections	highways
communication	computers	fiber optic cables
World Wide Web	web pages	hyperlinks
social	people	relationships
food web	species	predator-prey
software systems	functions	function calls
scheduling	tasks	precedence constraints
circuits	gates	wires

Graph Representation: Adjacency Matrix

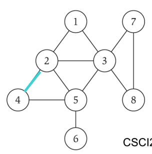
- n×n matrix with A_{uv} = 1 if (u, v) is an edge
  - Two representations of each edge (symmetric matrix)
  - Space?
  - Checking if (u, v) is an edge?
  - Identifying all edges?



	1	2	3	4	5	6	7	8
1	0	1	1	0	0	0	0	0
2	1	0	1	1	1	0	0	0
3	1	1	0	0	1	0	1	1
4	0	1	0	1	1	0	0	0
5	0	1	1	1	0	1	0	0
6	0	0	0	0	1	0	0	0
7	0	0	1	0	0	0	0	1
8	0	0	1	0	0	0	1	0

Graph Representation: Adjacency Matrix

- $n \times n$ matrix with $A_{uv} = 1$ if (u, v) is an edge
  - Two representations of each edge (symmetric matrix)
  - Space: $\Theta(n^2)$
  - Checking if (u, v) is an edge: $\Theta(1)$ time
  - Identifying all edges: $\Theta(n^2)$ time

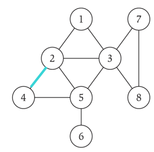


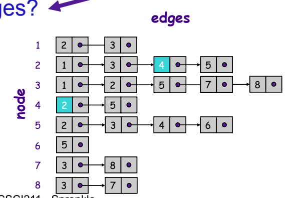
	1	2	3	4	5	6	7	8
1	0	1	1	0	0	0	0	0
2	1	0	1	1	1	0	0	0
3	1	1	0	0	1	0	1	1
4	0	1	0	1	1	0	0	0
5	0	1	1	1	0	1	0	0
6	0	0	0	0	1	0	0	0
7	0	0	1	0	0	0	0	1
8	0	0	1	0	0	0	1	0

Graph Representation: Adjacency List

- Node indexed array of lists
  - Two representations of each edge
  - Space?
  - Checking if (u, v) is an edge?
  - Identifying all edges?

What are the extremes?

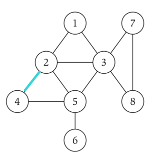


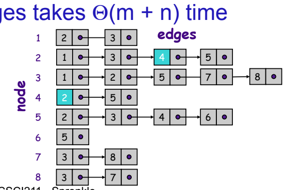


Graph Representation: Adjacency List

- Node indexed array of lists
  - Two representations of each edge
  - Space = $2m + n = O(m + n)$
  - Checking if (u, v) is an edge takes $O(deg(u))$ time
  - Identifying all edges takes $\Theta(m + n)$ time

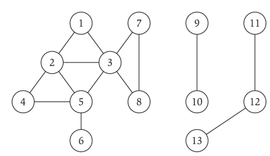
degree = number of neighbors of u





Paths and Connectivity

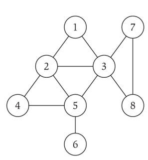
- Def. A ***path*** in an undirected graph $G = (V, E)$ is a sequence P of nodes $v_1, v_2, \ldots, v_{k-1}, v_k$
  - each consecutive pair v_i, v_{i+1} is joined by an edge in E
- Def. A path is ***simple*** if all nodes are *distinct*
- Def. An undirected graph is ***connected*** if $\forall$ pair of nodes u and v, there is a path between u and v



- *Short path*
- *Distance*

Cycles

- Def. A ***cycle*** is a path $v_1, v_2, \ldots, v_{k-1}, v_k$ in which $v_1 = v_k$, $k > 2$, and the first $k-1$ nodes are all distinct



cycle C = 1-2-4-5-3-1

Looking Ahead

- Reading: Starting Chapter 3
- Wednesday: notes about readings are due
- Friday: Problem Set 2
  - Start thinking about problems early