CSE 332 Autumn 2024
Lecture 13: Hashing 3

Nathan Brunelle

http://www.cs.uw.edu/332

Next topic: Hash Tables

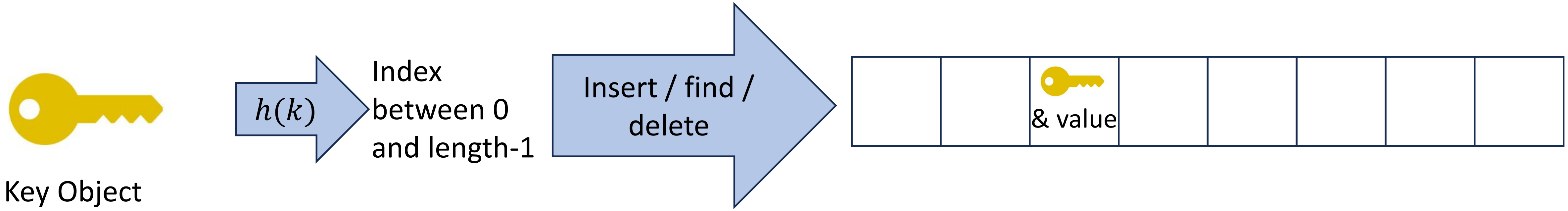
Data Structure	Time to insert	Time to find	Time to delete
Unsorted Array	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Unsorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Sorted Array	$\Theta(n)$	$\Theta(\log n)$	$\Theta(n)$
Sorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Binary Search Tree	$\Theta(\text{height})$	$\Theta(\text{height})$	$\Theta(\text{height})$
AVL Tree	$\Theta(\log n)$	$\Theta(\log n)$	$\Theta(\log n)$
Hash Table (Worst case)	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Hash Table (Expected and amortized)	$\Theta(1)$	$\Theta(1)$	$\Theta(1)$

Dictionary (Map) ADT

- Contents:
  - Sets of key+value pairs
  - ~~Keys must be comparable~~
- Operations:
  - insert(key, value)
    - Adds the (key,value) pair into the dictionary
    - If the key already has a value, overwrite the old value
      - Consequence: Keys cannot be repeated
  - find(key)
    - Returns the value associated with the given key
  - delete(key)
    - Remove the key (and its associated value)

Hash Tables

- Idea:
  - Have a small array to store information
  - Use a **hash function** to convert the key into an index
    - Hash function should “scatter” the keys, behave as if it randomly assigned keys to indices
  - Store key at the index given by the hash function
  - Do something if two keys map to the same place (should be very rare)
    - Collision resolution



Rehashing

- If your load factor λ gets too large, copy everything over to a larger hash table
  - To do this: make a new, larger array
  - Re-insert all items into the new hash table by reapplying the hash function
    - We need to reapply the hash function because items should map to a different index
  - New array should be "roughly" double the length (but probably still want it to be prime)
- What does "too large" mean?
  - For separate chaining, typically we want $\lambda < 2$
  - For open addressing, typically we want $\lambda < \frac{1}{2}$

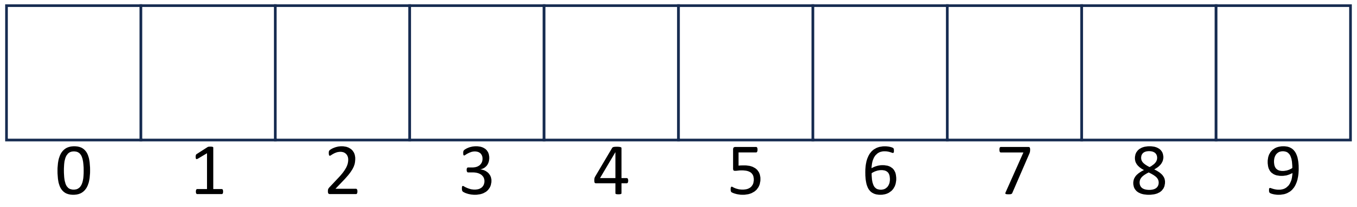
Linear Probing: Insert Procedure

- To insert k, v
  - Calculate $i = h(k)\ \%\ length$
  - If $table[i]$ is occupied then try $(i + 1)\%\ length$
  - If that is occupied try $(i + 2)\%\ length$
  - If that is occupied try $(i + 3)\%\ length$
  - …
  - $h(k) = k\%10$

		2	32	24	62	54			
0	1	2	3	4	5	6	7	8	9

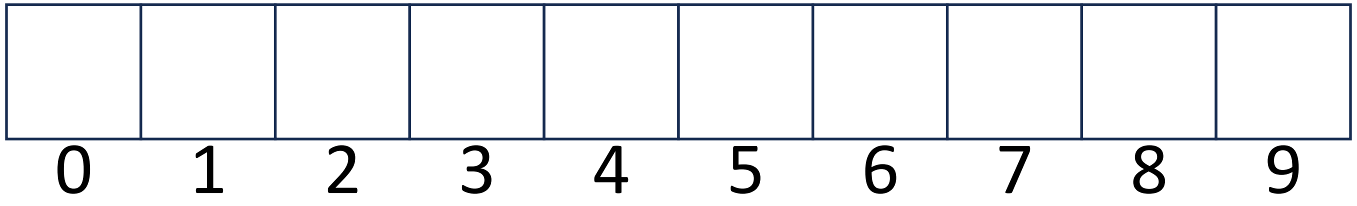
Linear Probing: Find

- To find key k
  - Calculate $i = h(k)\ \%\ length$
  - If $table[i]$ is occupied and does not contain k then look at $(i+1)\ \%\ length$
  - If that is occupied and does not contain k then look at $(i+2)\ \%\ length$
  - If that is occupied and does not contain k then look at $(i+3)\ \%\ length$
  - Repeat until you either find k or else you reach an empty cell in the table



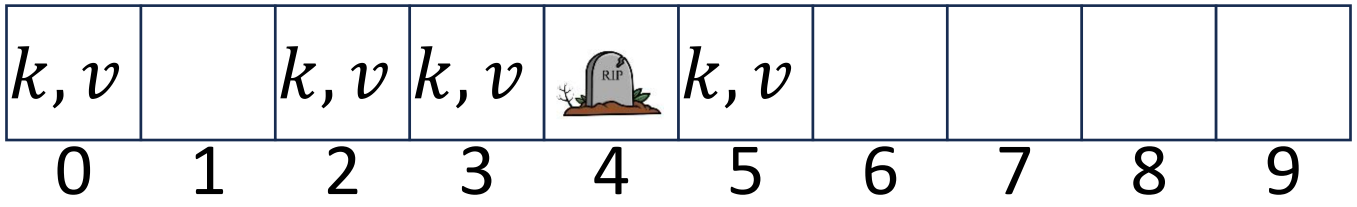
Linear Probing: Delete

- To delete key k, where $h(k) = i$
  - Assume it is present
- Beginning at index i, probe until we find k (call this location index j)
- Mark j as empty (e.g. null), then continue probing while doing the following until you find another empty index
  - If you come across a key which hashes to a value $\leq j$ then move that item to index j and update j.



Linear Probing: Delete

- Option 1: Fill in with items that hashed to before the empty slot
- Option 2: “Tombstone” deletion. Leave a special object that indicates an object was deleted from there
  - The tombstone does not act as an open space when finding (so keep looking after its reached)
  - When inserting you can replace a tombstone with a new item

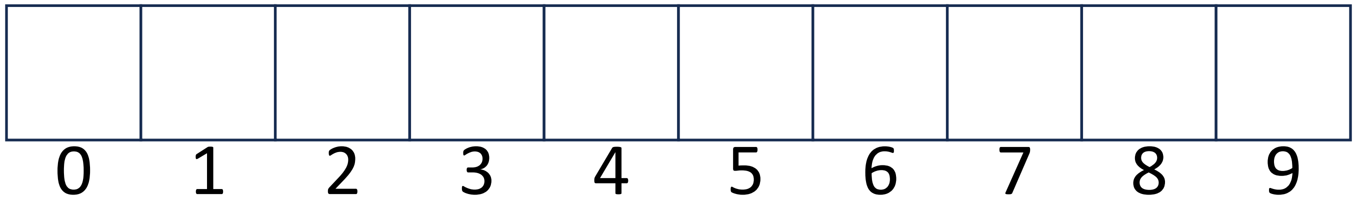


Downsides of Linear Probing

- What happens when λ approaches 1?
  - Get longer and longer contiguous blocks
  - A collision is guaranteed to grow a block
    - Larger blocks experience more collisions
    - Feedback loop!
- What happens when λ exceeds 1?
  - Impossible!
  - You can’t insert more stuff

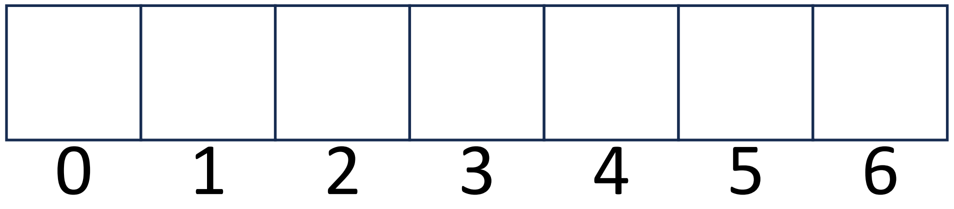
Quadratic Probing: Insert Procedure

- To insert k, v
  - Calculate $i = h(k) \; \% \; size$
  - If $table[i]$ is occupied then try $(i + 1^2) \% \; size$
  - If that is occupied try $(i + 2^2) \% \; size$
  - If that is occupied try $(i + 3^2) \% \; size$
  - If that is occupied try $(i + 4^2) \% \; size$
  - …



Quadratic Probing: Example

- Insert:
  - 76
  - 40
  - 48
  - 5
  - 55
  - 47



Using Quadratic Probing

- If you probe $tablesize$ times, you start repeating the same indices
- If $tablesize$ is prime and $\lambda < \frac{1}{2}$ then you're guaranteed to find an open spot in at most $tablesize/2$ probes

- Helps with the clustering problem of linear probing, but does not help if many things hash to the same value

Double Hashing: Insert Procedure

- Given h and g are both good hash functions
- To insert k, v
  - Calculate $i = h(k) \ \% \ size$
  - If $table[i]$ is occupied then try $\left(i + g(k)\right) \ \% \ size$
  - If that is occupied try $\left(i + 2 \cdot g(k)\right)\% \ size$
  - If that is occupied try $\left(i + 3 \cdot g(k)\right)\% \ size$
  - If that is occupied try $\left(i + 4 \cdot g(k)\right)\% \ size$
  - …

0	1	2	3	4	5	6	7	8	9

Sorting

- Rearrangement of items into some defined sequence
  - Usually: reordering a list from smallest to largest according to some metric
- Why sort things?

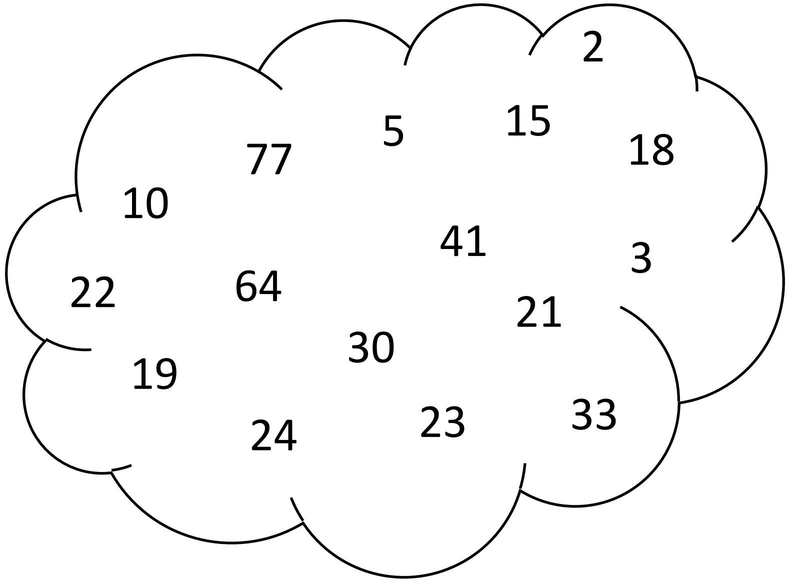
More Formal Definition

- Input:
  - An array A of items
  - A comparison function for these items
    - Given two items x and y, we can determine whether $x < y$, $x > y$, or $x = y$
- Output:
  - A permutation of A such that if $i \leq j$ then $A[i] \leq A[j]$
  - Permutation: a sequence of the same items but perhaps in a different order

Sorting “Landscape”

- There is no singular best algorithm for sorting
- Some are faster, some are slower
- Some use more memory, some use less
- Some are super extra fast if your data matches particular assumptions
- Some have other special properties that make them valuable
- No sorting algorithm can have only all the “best” attributes

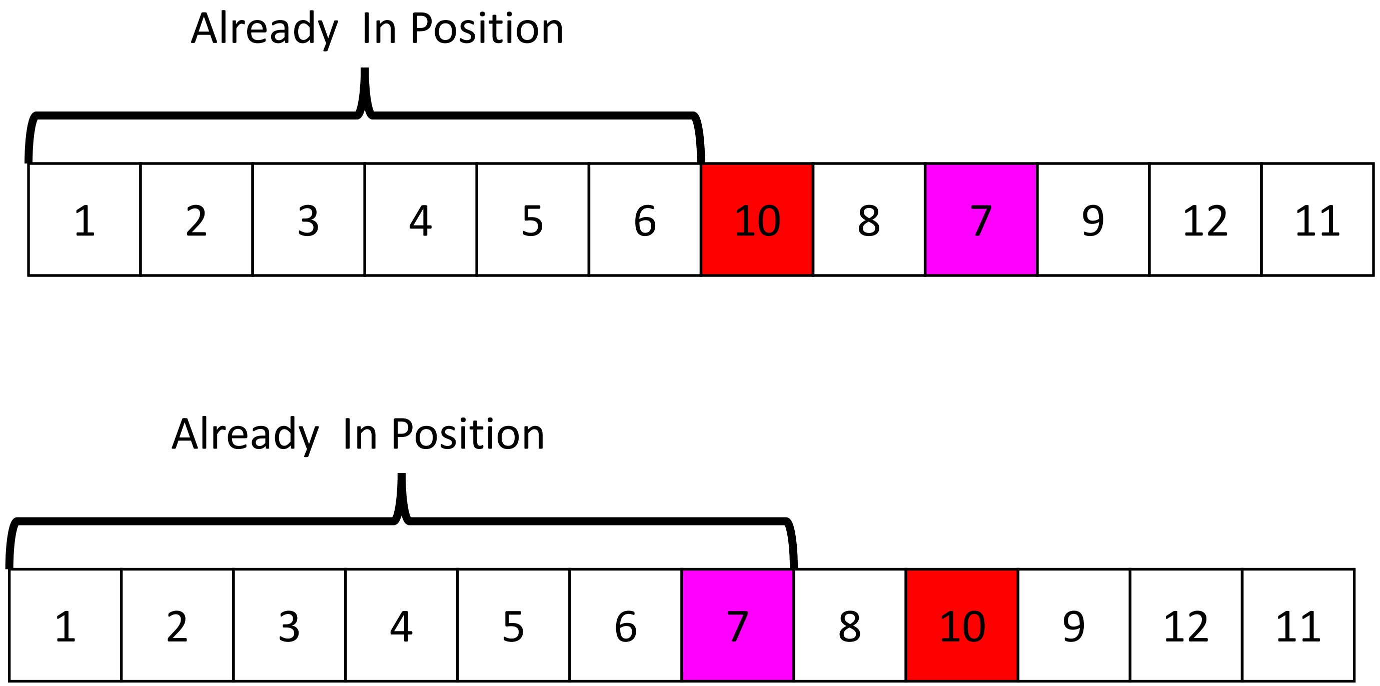
“Moving Day” Sorting Algorithm



0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Selection Sort

- Idea: Find the next smallest element, swap it into the next index in the array



Selection Sort

- Swap the thing at index 0 with the smallest thing in the array
- Swap the thing at index 1 with the smallest thing after index 0
- …
- Swap the thing at index i with the smallest thing after index $i-1$

```
for (i=0; i<a.length; i++){
        smallest = i;
        for (j=i; j<a.length; j++){
                if (a[j]<a[smallest]){ smallest=j;}
        }
        temp = a[i];
        a[i] = a[smallest];
        a[smallest] = a[i];
}
```

Running Time:

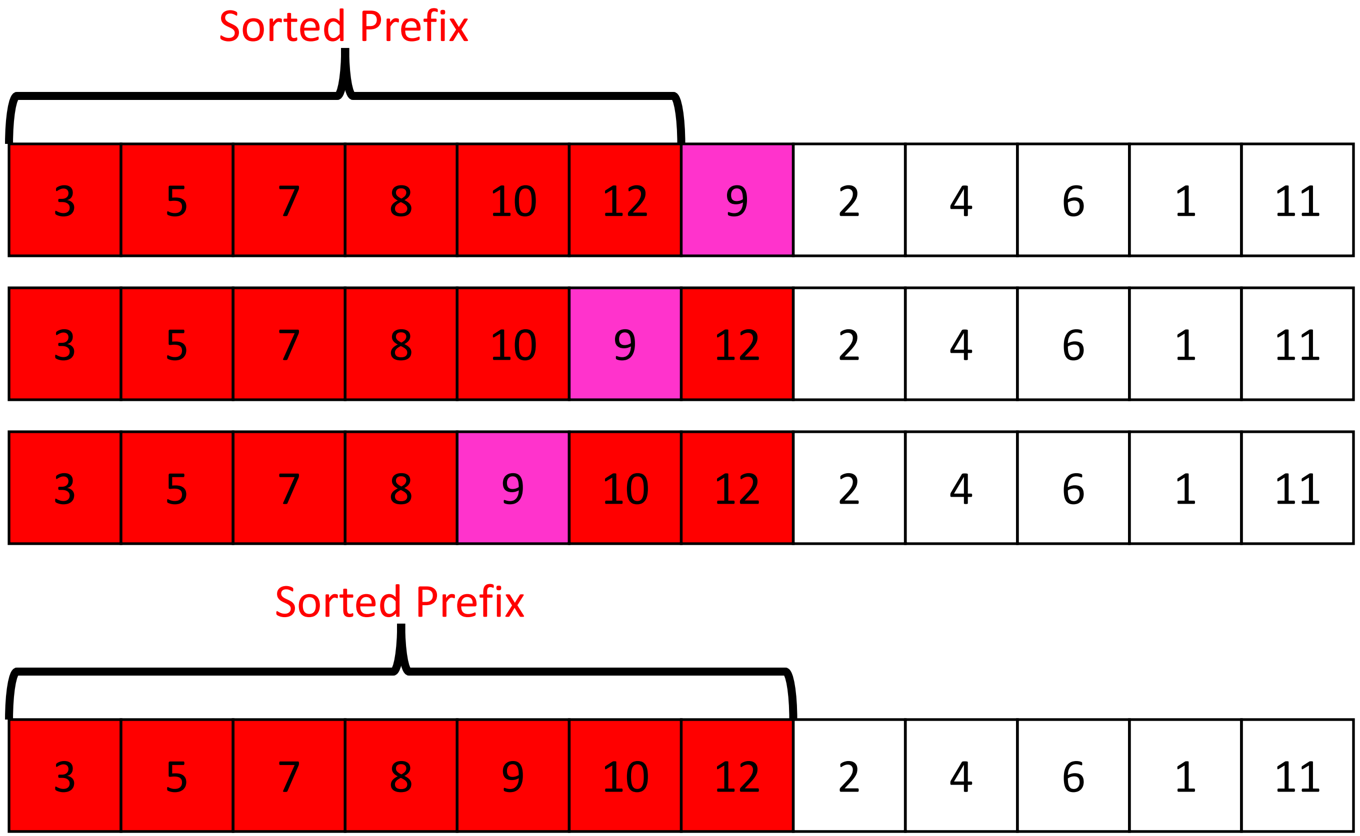
Worst Case: $\Theta(\cdot)$

Best Case: $\Theta(\cdot)$

10	77	5	15	2	22	64	41	18	19	30	21	3	24	23	33
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Insertion Sort

- Idea: Maintain a sorted list prefix, extend that prefix by “inserting” the next element



Insertion Sort

- If the items at index 0 and 1 are out of order, swap them
- Keep swapping the item at index 2 with the thing to its left as long as the left thing is larger
- …
- Keep swapping the item at index i with the thing to its left as long as the left thing is larger

```
for (i=1; i<a.length; i++){
    prev = i-1;
    while(a[i] < a[prev] && prev > -1){
        temp = a[i];
        a[i] = a[prev];
        a[prev] = a[i];
        i--;
        prev--;
    }
}
```

Running Time:

Worst Case: $\Theta(\cdot)$

Best Case: $\Theta(\cdot)$

10	77	5	15	2	22	64	41	18	19	30	21	3	24	23	33
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Aside: Bubble Sort – we won’t cover it

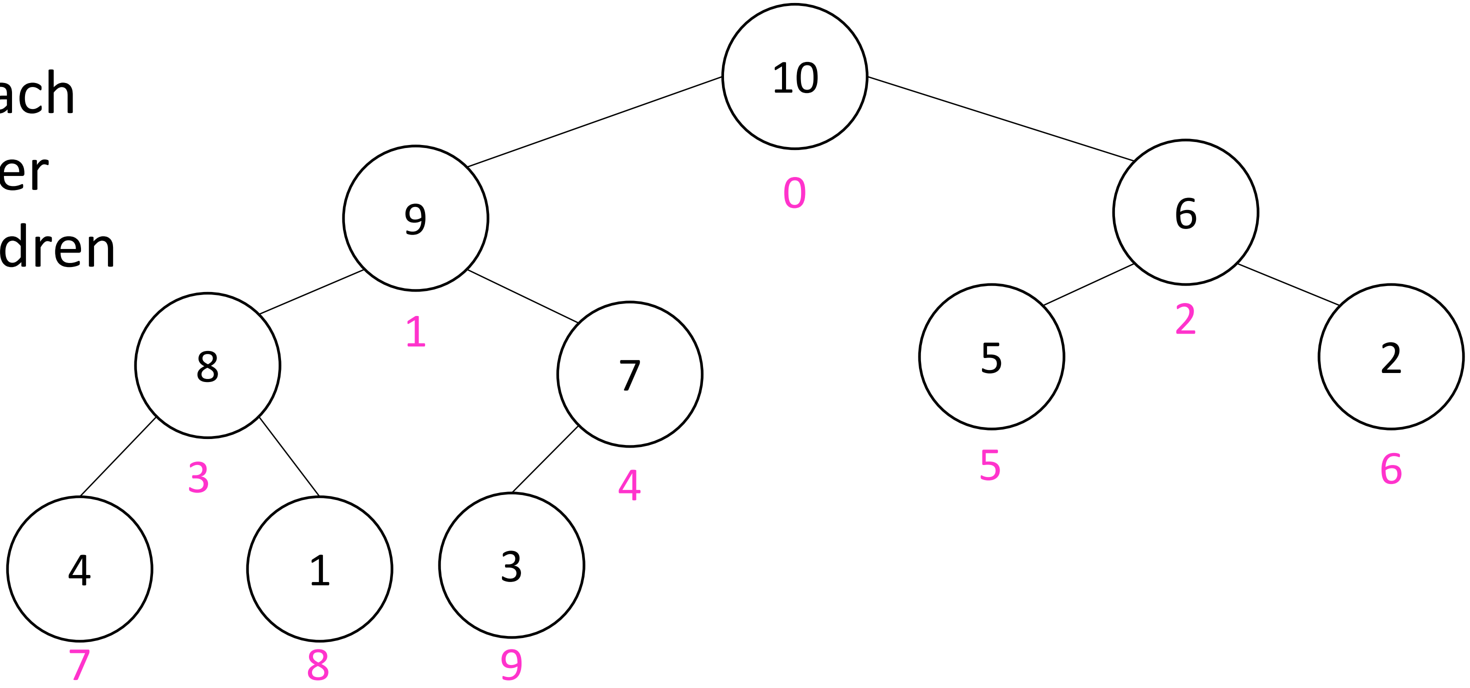
"the bubble sort seems to have nothing to recommend it, except a catchy name and the fact that it leads to some interesting theoretical problems” –Donald Knuth, The Art of Computer Programming

Heap Sort

- Idea: Build a maxHeap, repeatedly delete the max element from the heap to build sorted list Right-to-Left

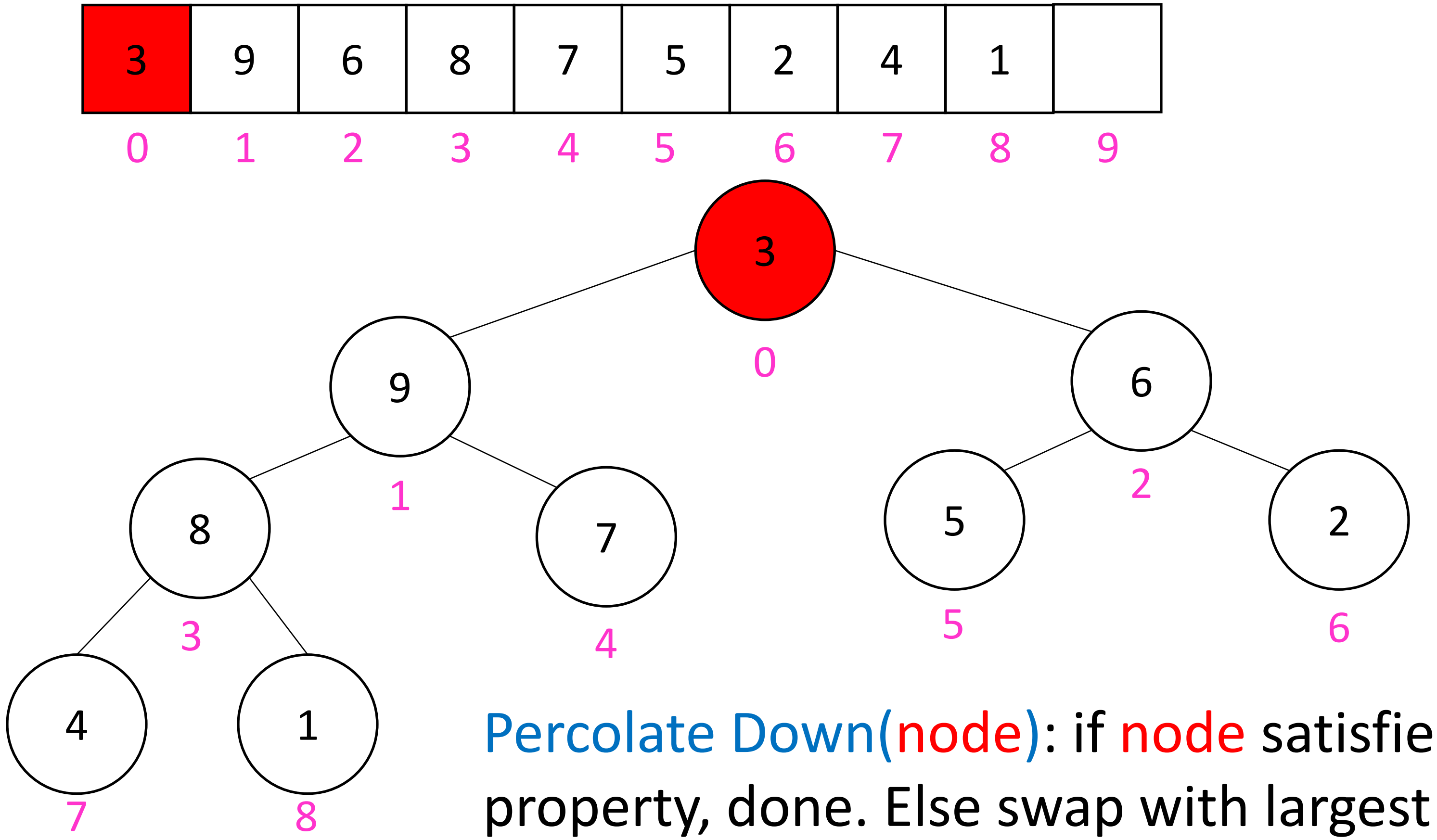
10	9	6	8	7	5	2	4	1	3
0	1	2	3	4	5	6	7	8	9

Max Heap Property: Each node is larger than its children



Heap Sort

- Remove the Max element (i.e. the root) from the Heap: replace with last element, call percolateDown(root)



Percolate Down(node): if node satisfies heap property, done. Else swap with largest child and repeat on that subtree

Heap Sort

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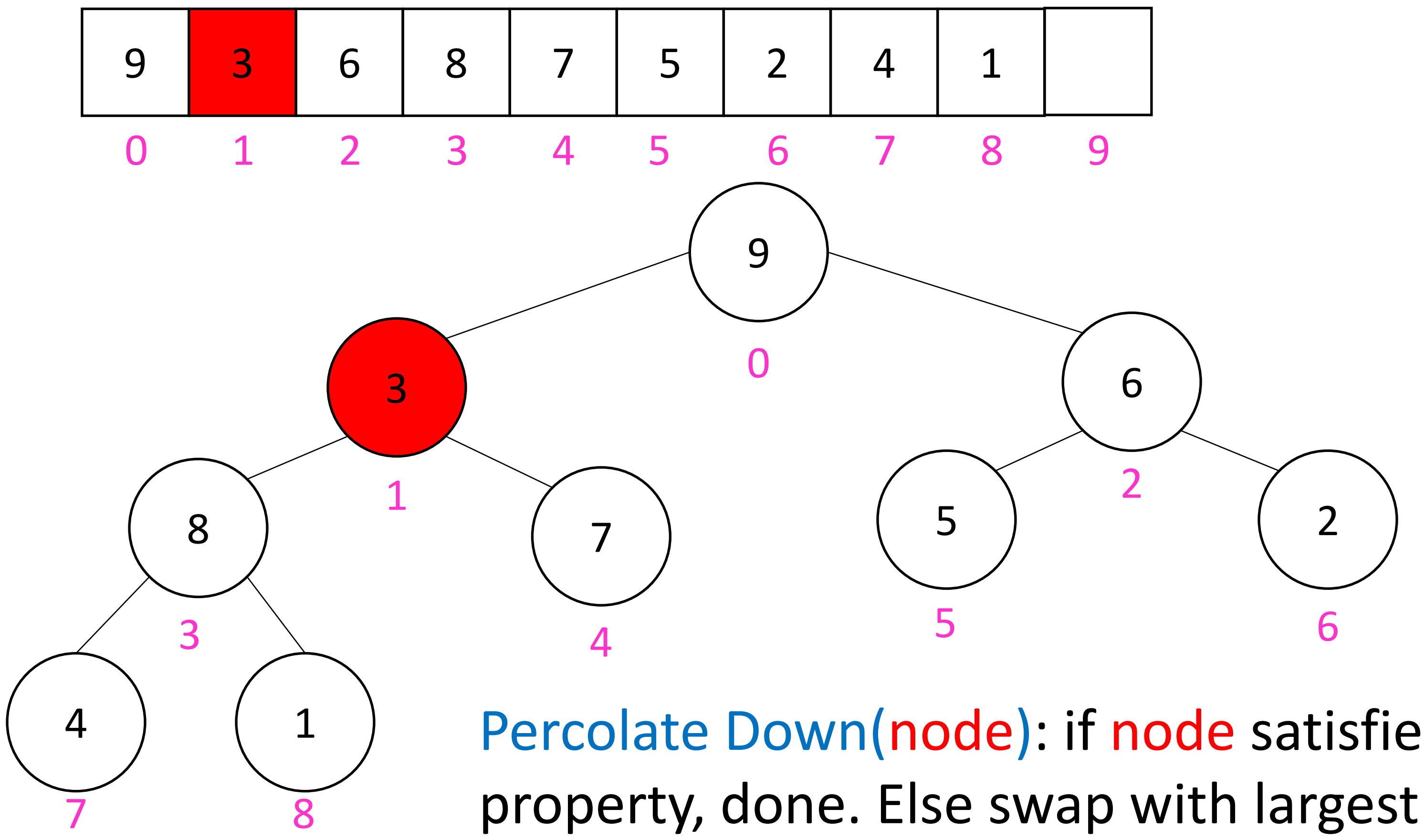

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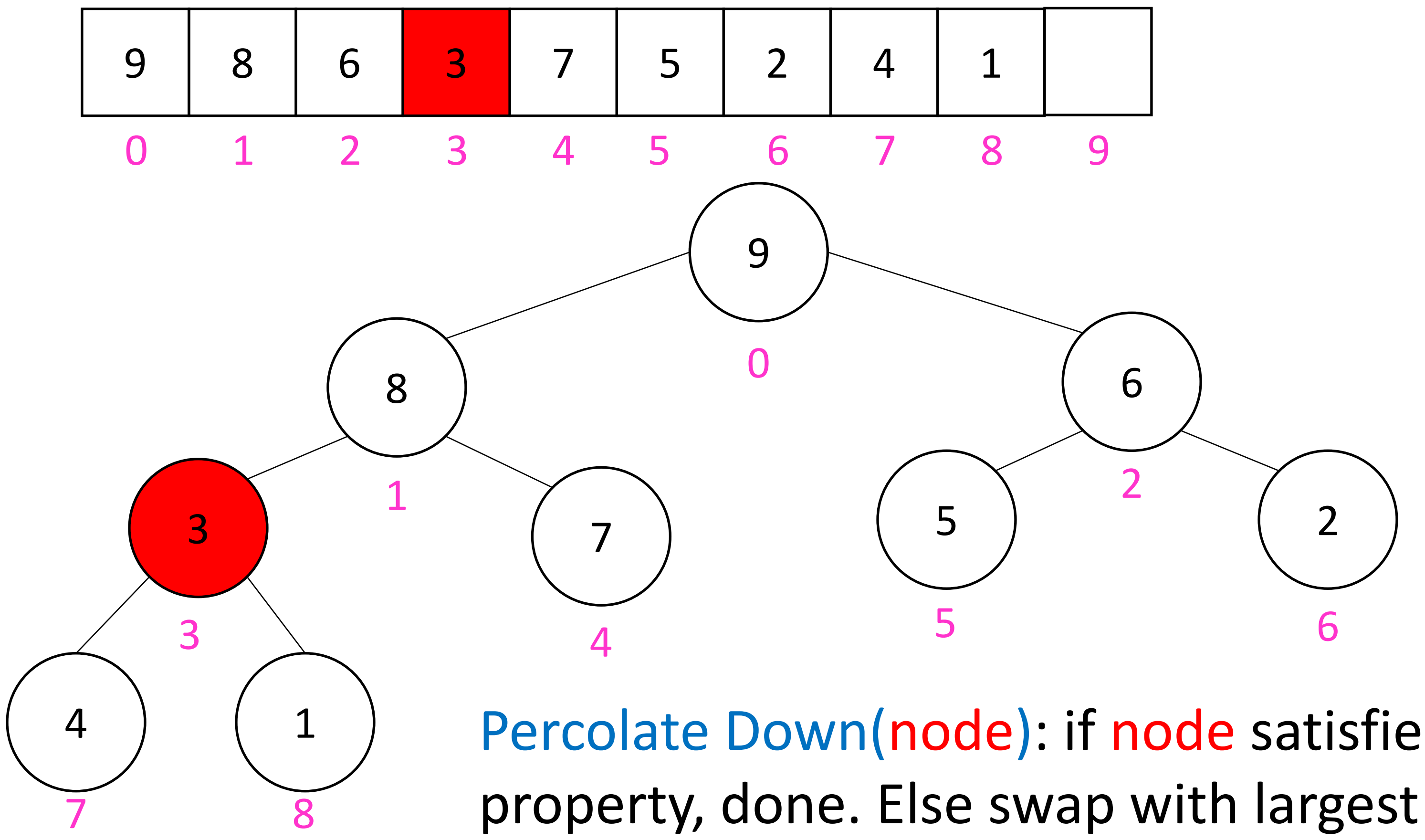

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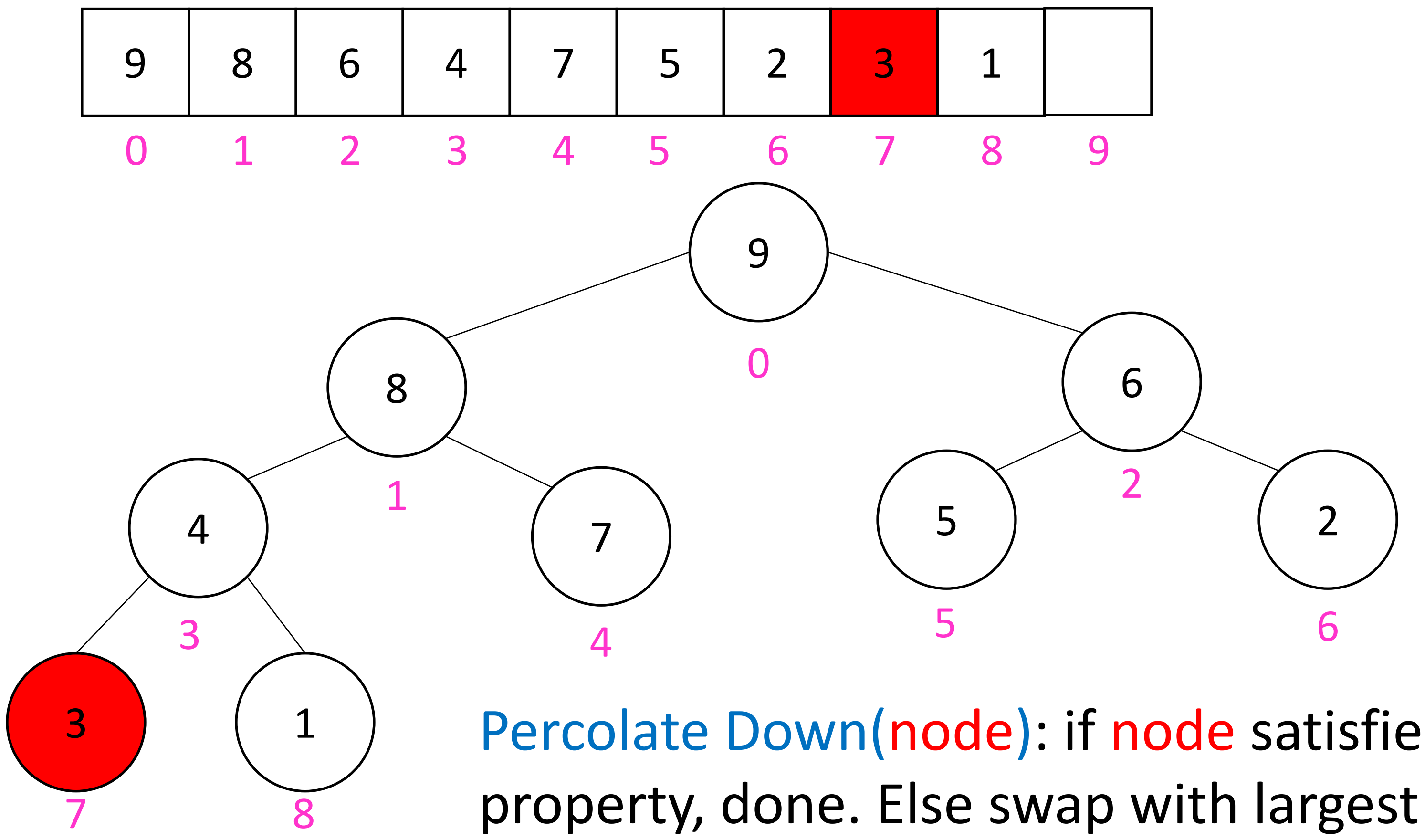


Percolate Down(node): if node satisfies heap property, done. Else swap with largest child and repeat on that subtree

Heap Sort

- Build a heap
- Call deleteMax
- Put that at the end of the array

```
myHeap = buildHeap(a);
for (int i = a.length-1; i>=0; i--){
    item = myHeap.deleteMax();
    a[i] = item;
}
```

Running Time:

Worst Case: $\Theta(\cdot)$

Best Case: $\Theta(\cdot)$

“In Place” Sorting Algorithm

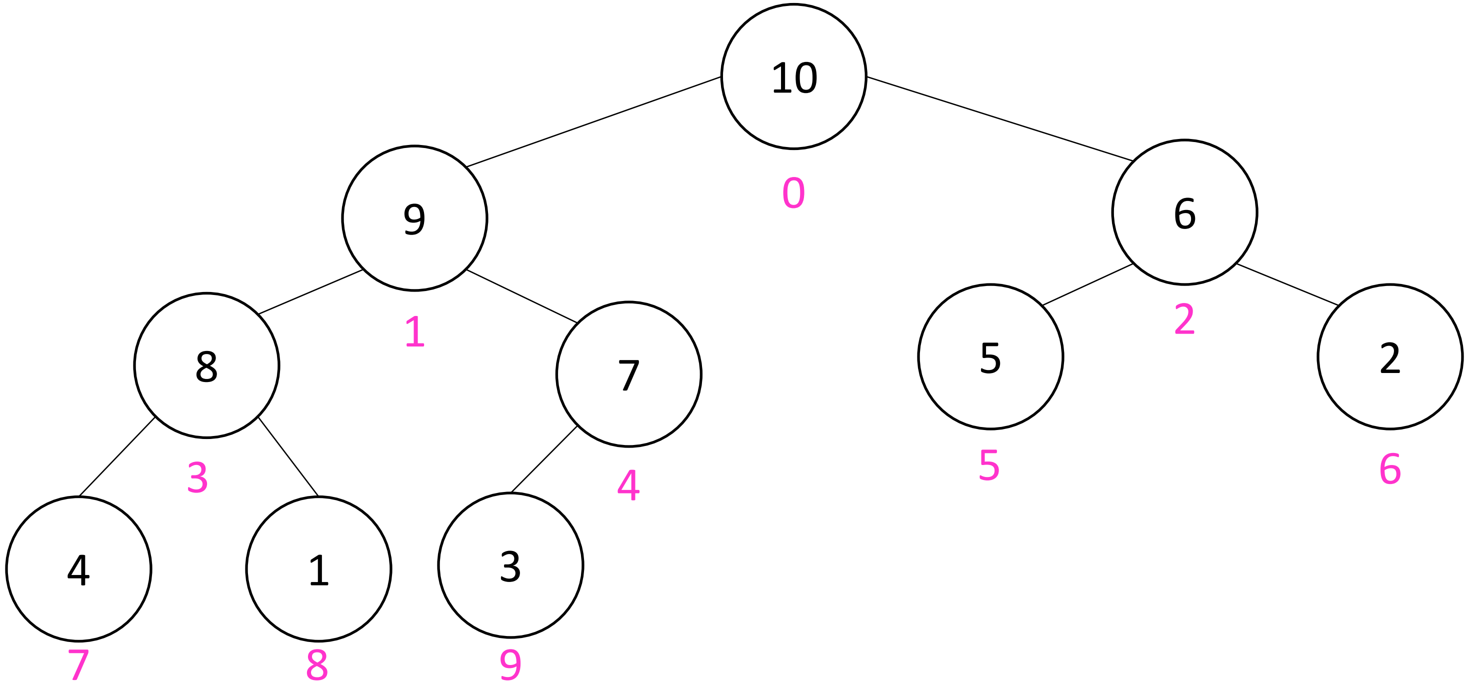
- A sorting algorithm which requires no extra data structures
- Idea: It sorts items just by swapping things in the same array given
- Definition: it only uses $\Theta(1)$ extra space

- Selection sort: In Place!
- Insertion sort: In Place!
- Heap sort: Not In Place!
  - But we can fix that!

In Place Heap Sort

- Idea: When “removing” an element from the heap, swap it with the last item of the heap then “pretend” the heap is one item shorter

10	9	6	8	7	5	2	4	1	3
0	1	2	3	4	5	6	7	8	9



Heap Sort

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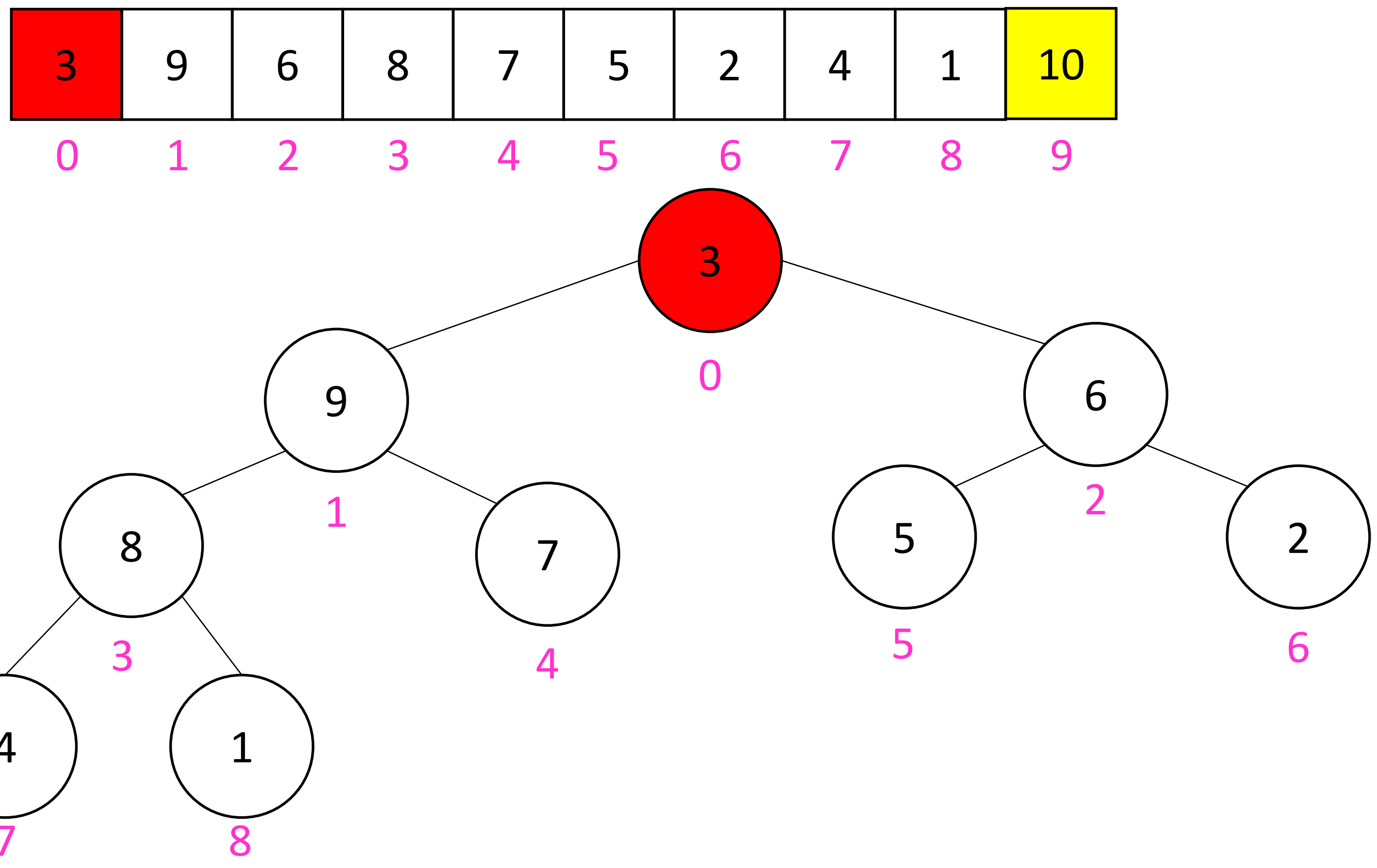
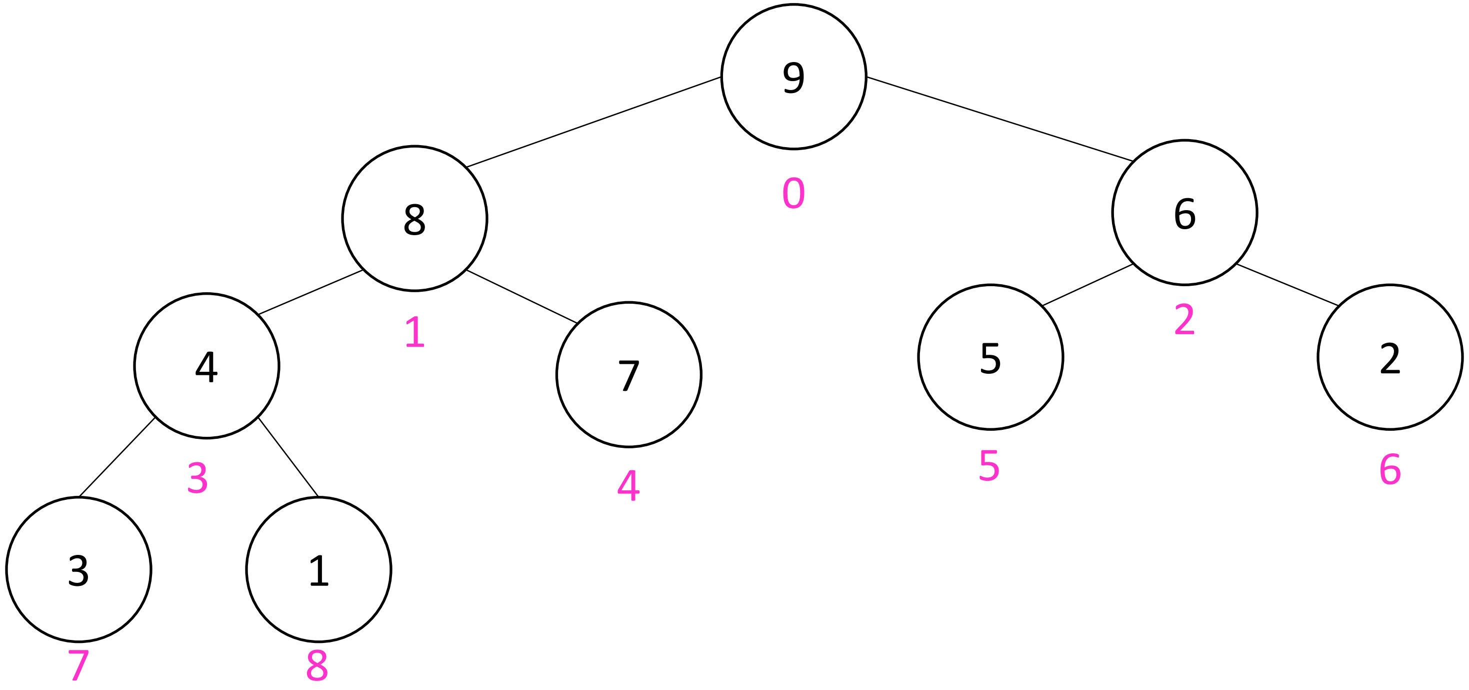


Heap Sort

- Idea: When "removing" an element from the heap, swap it with the last item of the heap then "pretend" the heap is one item shorter

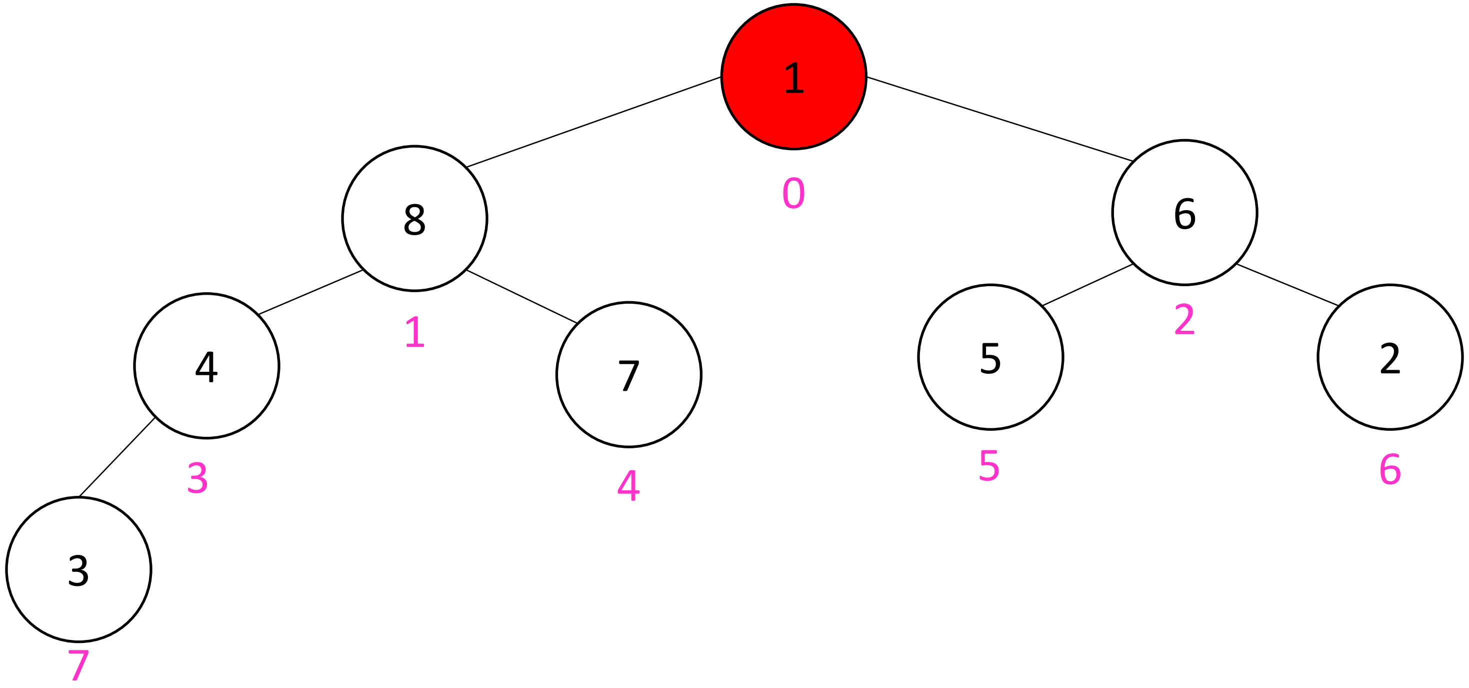
9	8	6	4	7	5	2	3	1	10
0	1	2	3	4	5	6	7	8	9



Heap Sort

- Idea: When “removing” an element from the heap, swap it with the last item of the heap then “pretend” the heap is one item shorter

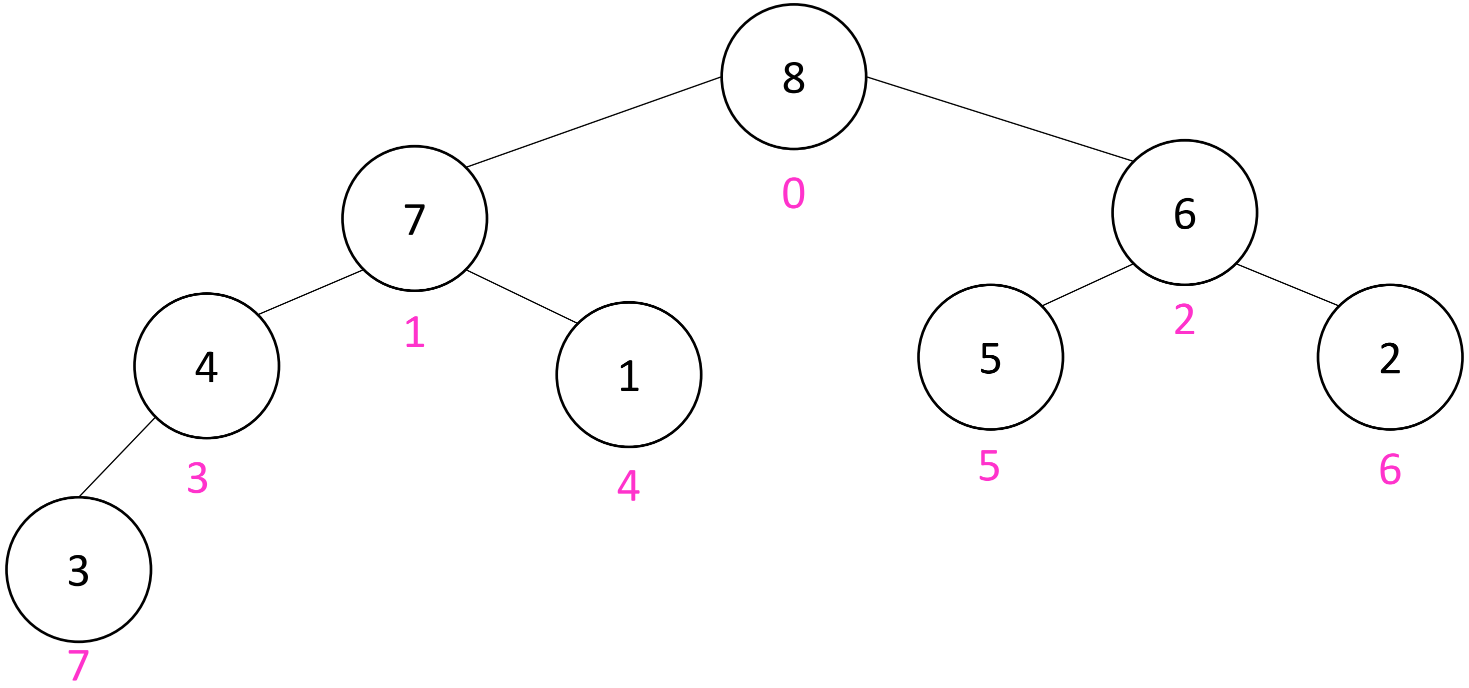
1	8	6	4	7	5	2	3	9	10
0	1	2	3	4	5	6	7	8	9



Heap Sort

- Idea: When “removing” an element from the heap, swap it with the last item of the heap then “pretend” the heap is one item shorter

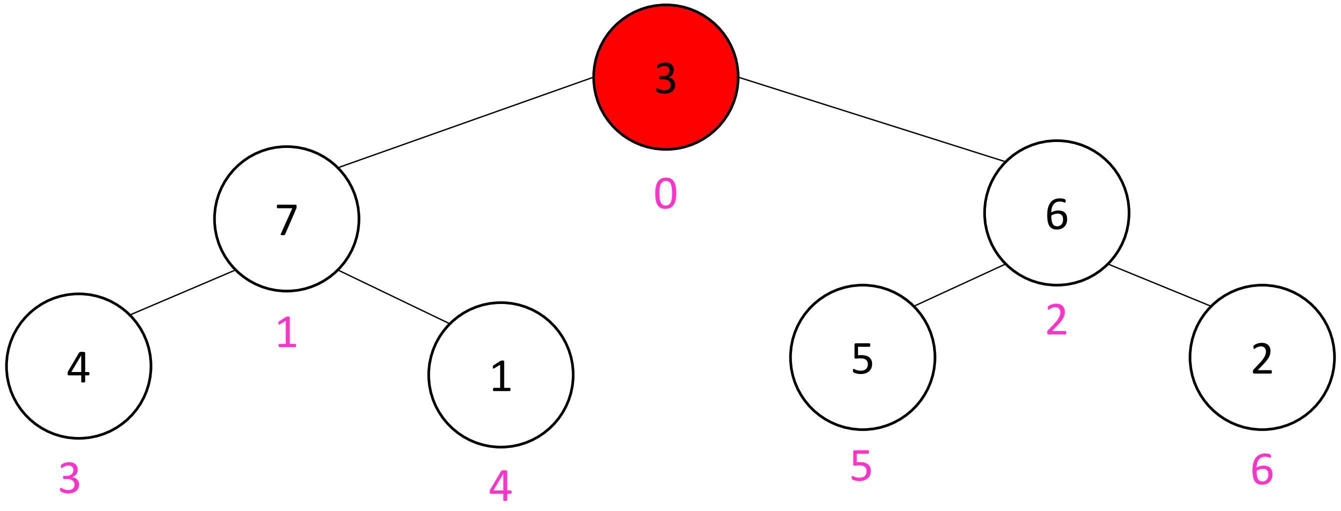
1	8	6	4	7	5	2	3	9	10
0	1	2	3	4	5	6	7	8	9



Heap Sort

- Idea: When "removing" an element from the heap, swap it with the last item of the heap then "pretend" the heap is one item shorter

3	8	6	4	7	5	2	8	9	10
0	1	2	3	4	5	6	7	8	9



Heap Sort

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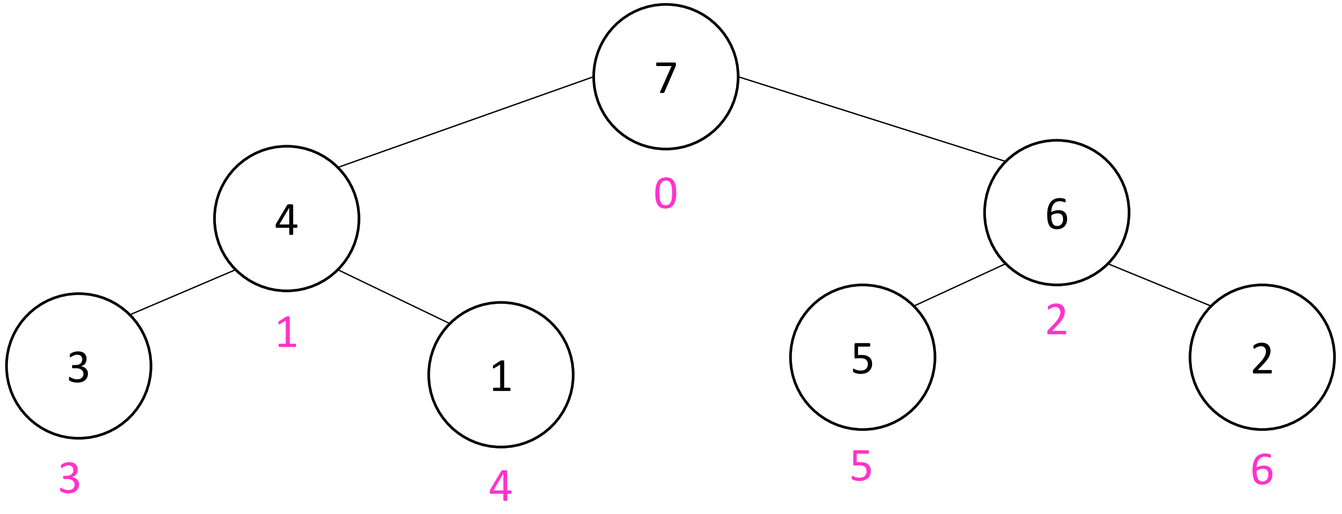
3	8	6	4	7	5	2	8	9	10
0	1	2	3	4	5	6	7	8	9



In Place Heap Sort

- Build a heap using the same array (Floyd's build heap algorithm works)
- Call deleteMax
- Put that at the end of the array

```
buildHeap(a);
for (int i = a.length-1; i>=0; i--){
	temp=a[i]
	a[i] = a[0];
	a[0] = temp;
	percolateDown(0);
}
```

Running Time:

Worst Case: $\Theta(\cdot)$

Best Case: $\Theta(\cdot)$

Floyd’s buildHeap method

- Working towards the root, one row at a time, percolate down

```
buildHeap(){
    for(int i = size; i>0; i--){
        percolateDown(i);
    }
}
```