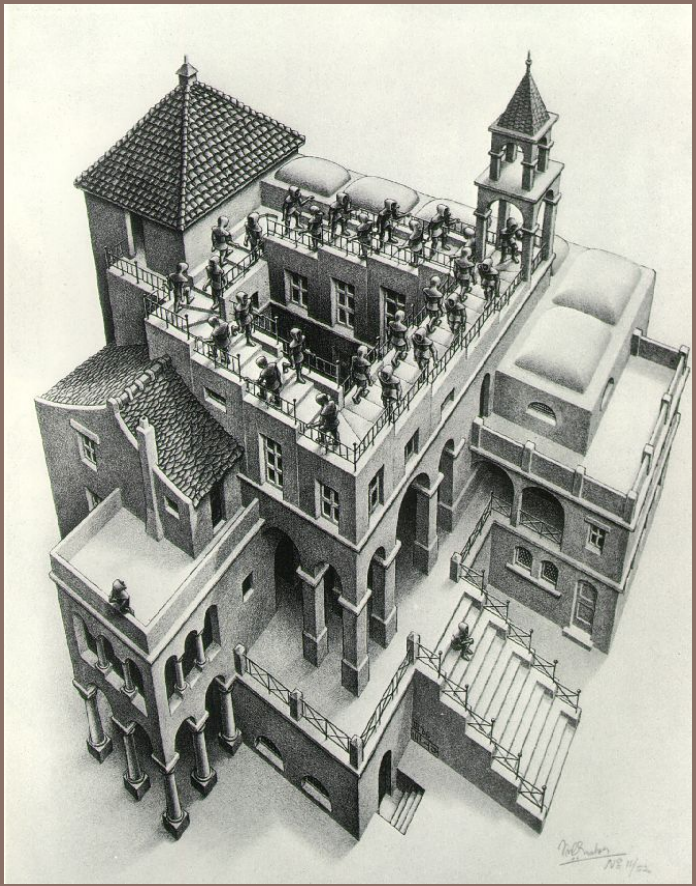


PRIORITY QUEUES AND HEAPS

Lecture 16
CS2110 Fall 2014

Reminder: A4 Collision Detection

- Due tonight by midnight

Readings and Homework

Read Chapter 26 "A Heap Implementation" to learn about heaps

Exercise: Salespeople often make matrices that show all the great features of their product that the competitor's product lacks. Try this for a heap versus a BST. First, try and sell someone on a BST: List some desirable properties of a BST that a heap lacks. Now be the heap salesperson: List some good things about heaps that a BST lacks. Can you think of situations where you would favor one over the other?

With ZipUltra heaps, you've got it made in the shade my friend!

The Bag Interface

A Bag:

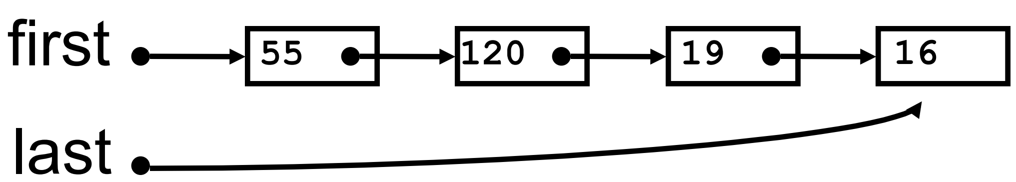
```
interface Bag<E> {
   void insert(E obj);
   E extract(); //extract some element
   boolean isEmpty();
}
```

Like a Set except that a value can be in it more than once. Example: a bag of coins

Refinements of Bag: Stack, Queue, PriorityQueue

Stacks and Queues as Lists

- Stack (LIFO) implemented as list
  - **`insert()`**, **`extract()`** from front of list
- Queue (FIFO) implemented as list
  - **`insert()`** on back of list, **`extract()`** from front of list
- These operations are O(1)



Priority Queue

- A `Bag` in which data items are `Comparable`
- *lesser* elements (as determined by `compareTo()`) have *higher* priority
- `extract()` returns the element with the highest priority = least in the `compareTo()` ordering
- break ties arbitrarily

Examples of Priority Queues

Scheduling jobs to run on a computer
default priority = arrival time
priority can be changed by operator

Scheduling events to be processed by an event handler
priority = time of occurrence

Airline check-in
first class, business class, coach
FIFO within each class

java.util.PriorityQueue<E>


```
boolean add(E e) {...} //insert an element (insert)

void clear() {...} //remove all elements

E peek() {...} //return min element without removing
               //(null if empty)

E poll() {...} //remove min element (extract)
               //(null if empty)

int size() {...}
```

Priority Queues as Lists

- Maintain as unordered list
  - **`insert()`** put new element at front – O(1)
  - **`extract()`** must search the list – O(n)

- Maintain as ordered list
  - **`insert()`** must search the list – O(n)
  - **`extract()`** get element at front – O(1)

- In either case, $O(n^2)$ to process n elements

Can we do better?

Important Special Case

- Fixed number of priority levels 0,...,p – 1
- FIFO within each level
- Example: airline check-in

- **`insert()`** – insert in appropriate queue – O(1)
- **`extract()`** – must find a nonempty queue – O(p)

Heaps

- A *heap* is a concrete data structure that can be used to implement priority queues
- Gives better complexity than either ordered or unordered list implementation:
  - **`insert()`:** O(log n)
  - **`extract()`:** O(log n)
- O(n log n) to process n elements
- Do not confuse with *heap memory*, where the Java virtual machine allocates space for objects – different usage of the word *heap*

Heaps

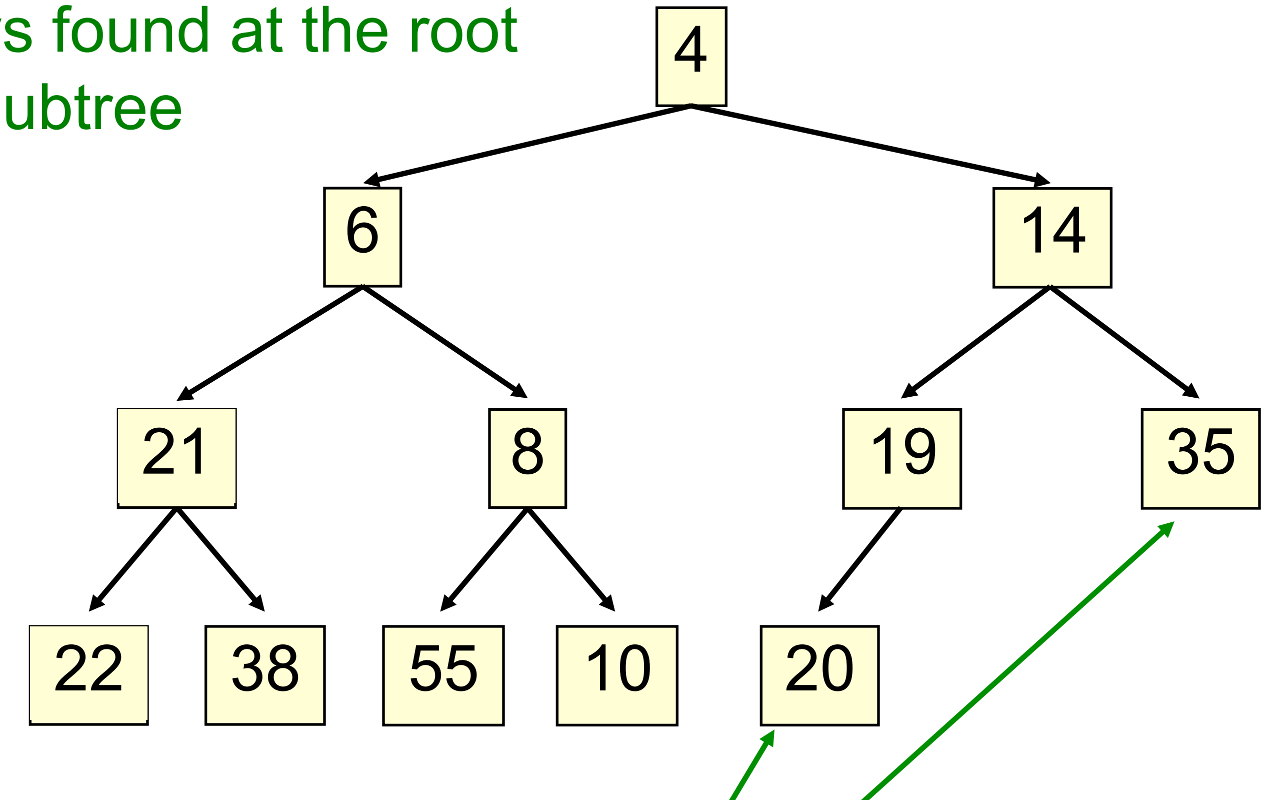
- Binary tree with data at each node
- Satisfies the *Heap Order Invariant*:

> The least (highest priority) element of any subtree is found at the root of that subtree.

- Size of the heap is “fixed” at *n*. (But can usually double n if heap fills up)

Heaps

Smallest element in any subtree
is always found at the root
of that subtree



Note: 19, 20 < 35: Smaller elements
can be deeper in the tree!

Examples of Heaps

- Ages of people in family tree
  - parent is always older than children, but you can have an uncle who is younger than you
- Salaries of employees of a company
  - bosses generally make more than subordinates, but a VP in one subdivision may make less than a Project Supervisor in a different subdivision

Balanced Heaps

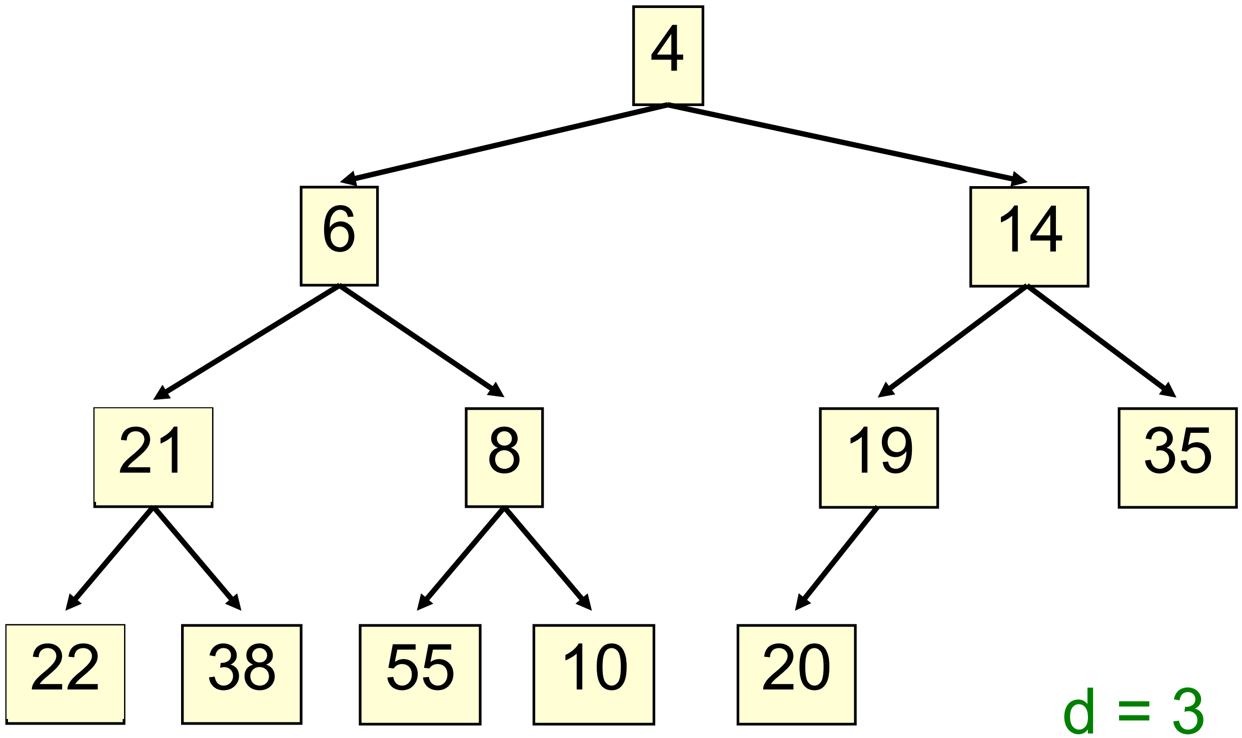
These add two restrictions:

1. Any node of depth < d – 1 has exactly 2 children, where d is the height of the tree

– implies that any two maximal paths (path from a root to a leaf) are of length d or d – 1, and the tree has at least 2^d nodes

- All maximal paths of length d are to the left of those of length d – 1

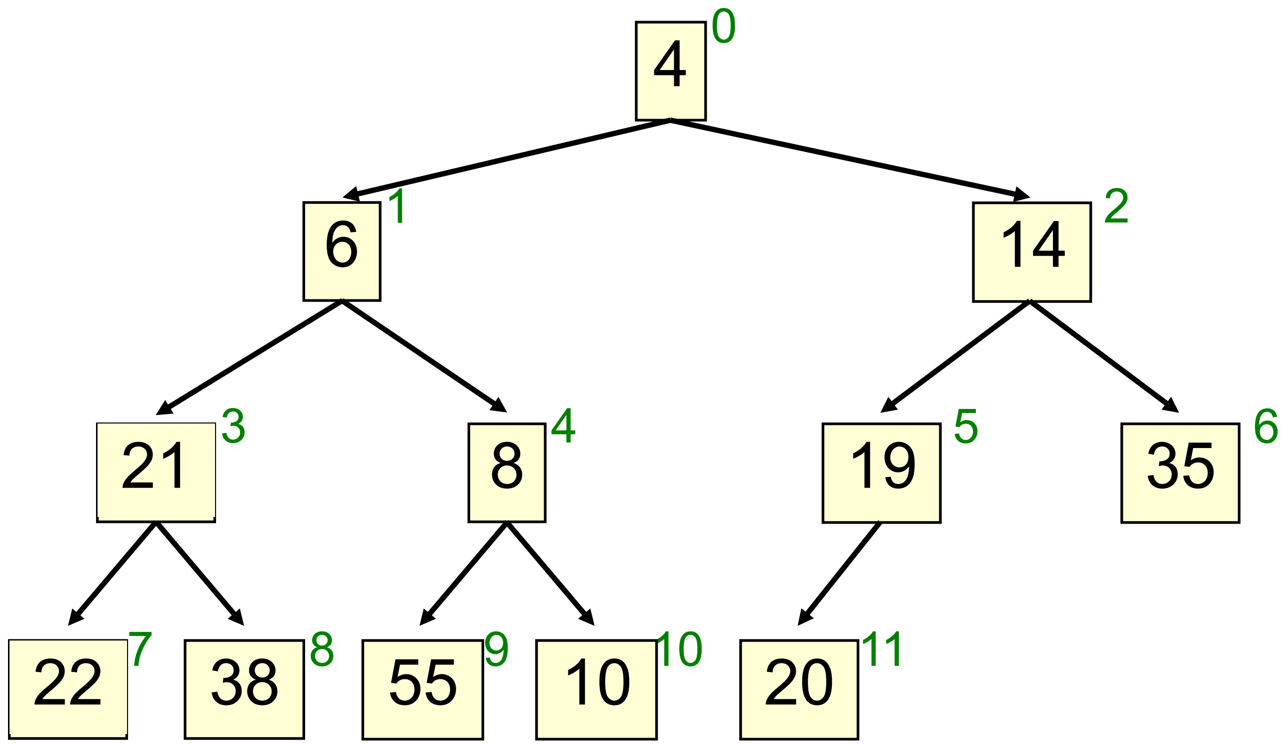
Example of a Balanced Heap



Store in an ArrayList or Vector

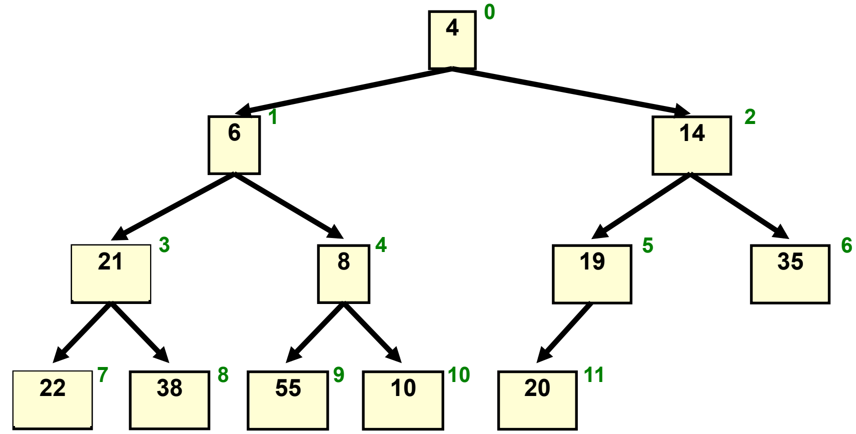
- Elements of the heap are stored in the array in order, going across each level from left to right, top to bottom
- The children of the node at array index n are at indices 2n + 1 and 2n + 2
- The parent of node n is node (n – 1)/2

Store in an ArrayList or Vector



children of node n are found at 2n + 1 and 2n + 2

Store in an ArrayList or Vector



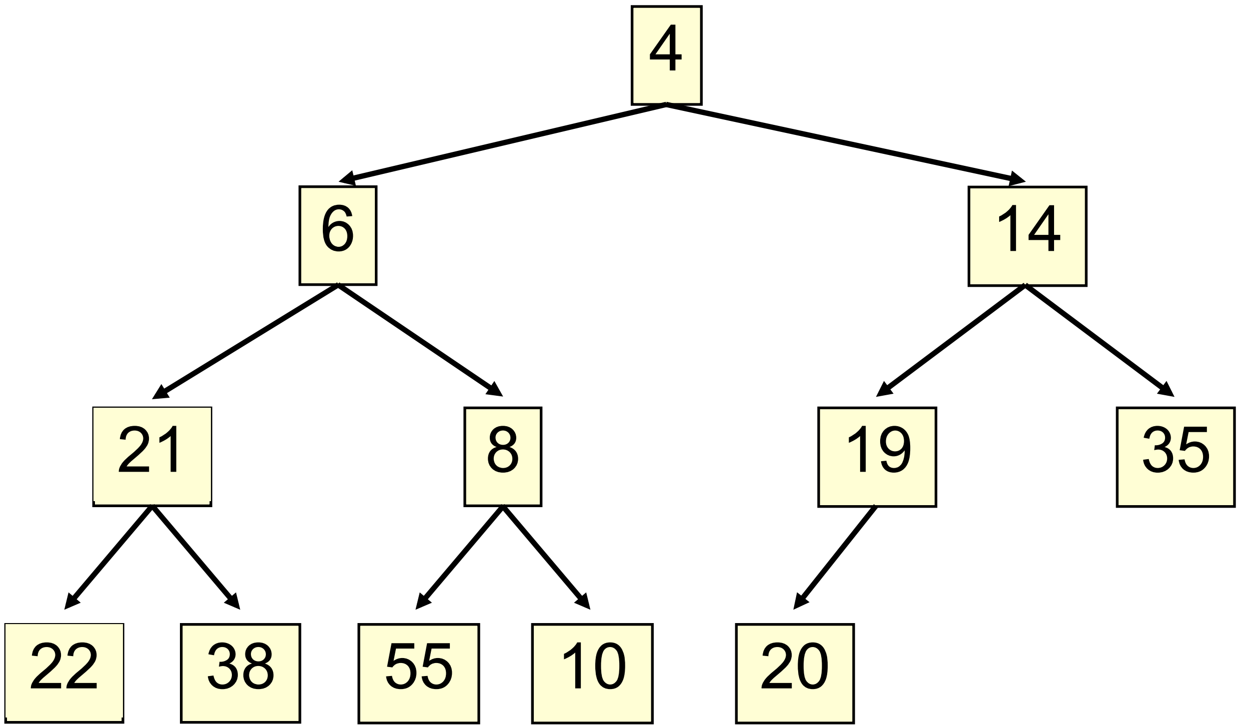
0	1	2	3	4	5	6	7	8	9	10	11
4	6	14	21	8	19	35	22	38	55	10	20

children of node n are found at 2n + 1 and 2n + 2

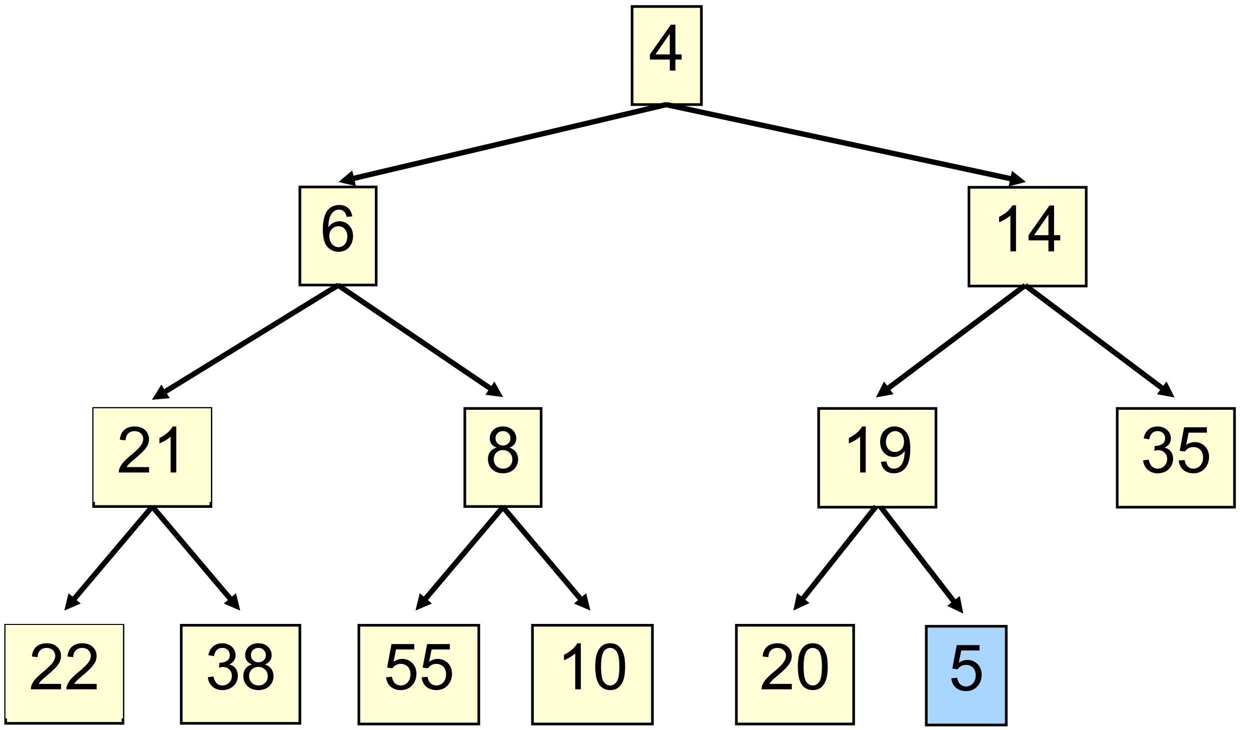
`insert()`

- Put the new element at the end of the array
- If this violates heap order because it is smaller than its parent, swap it with its parent
- Continue swapping it up until it finds its rightful place
- The heap invariant is maintained!

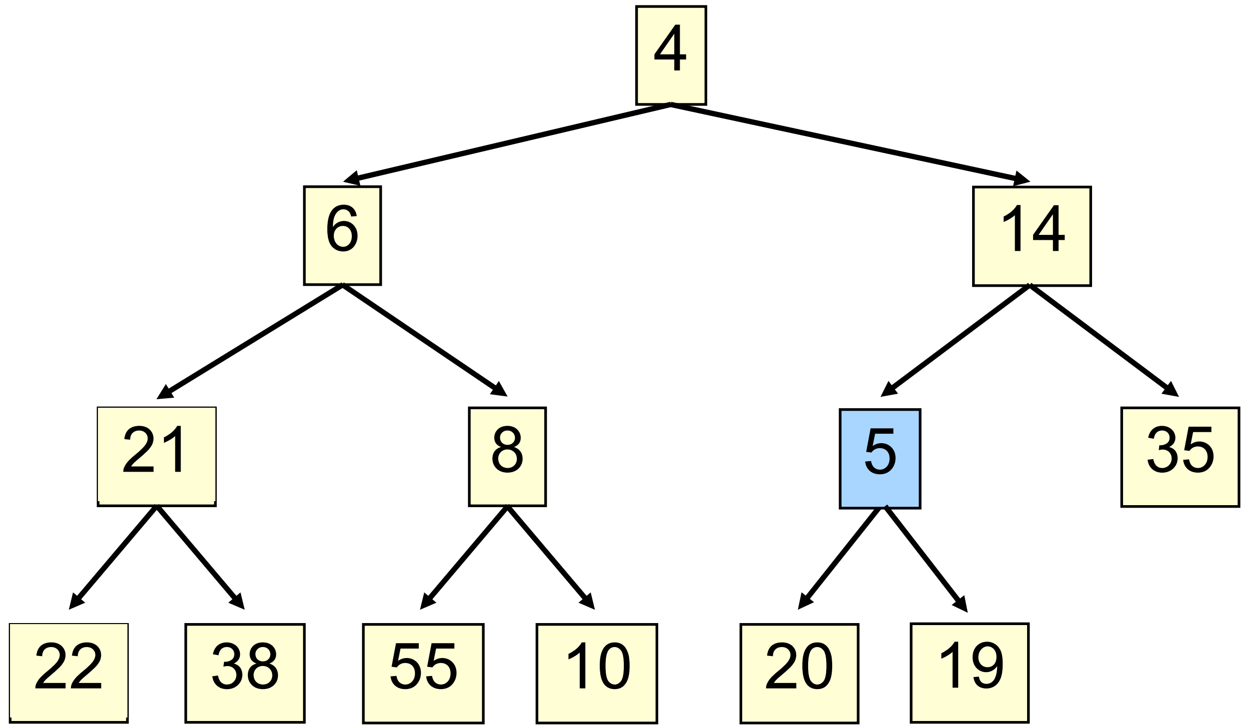
`insert()`



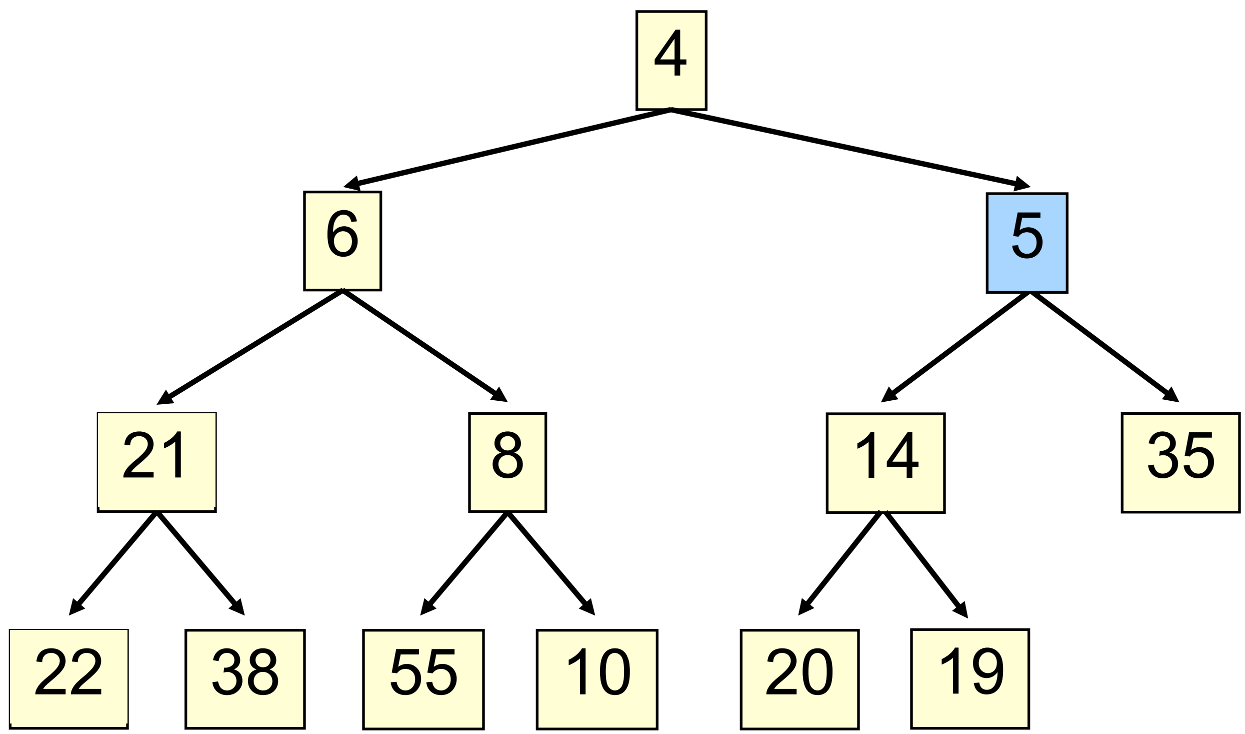
`insert()`



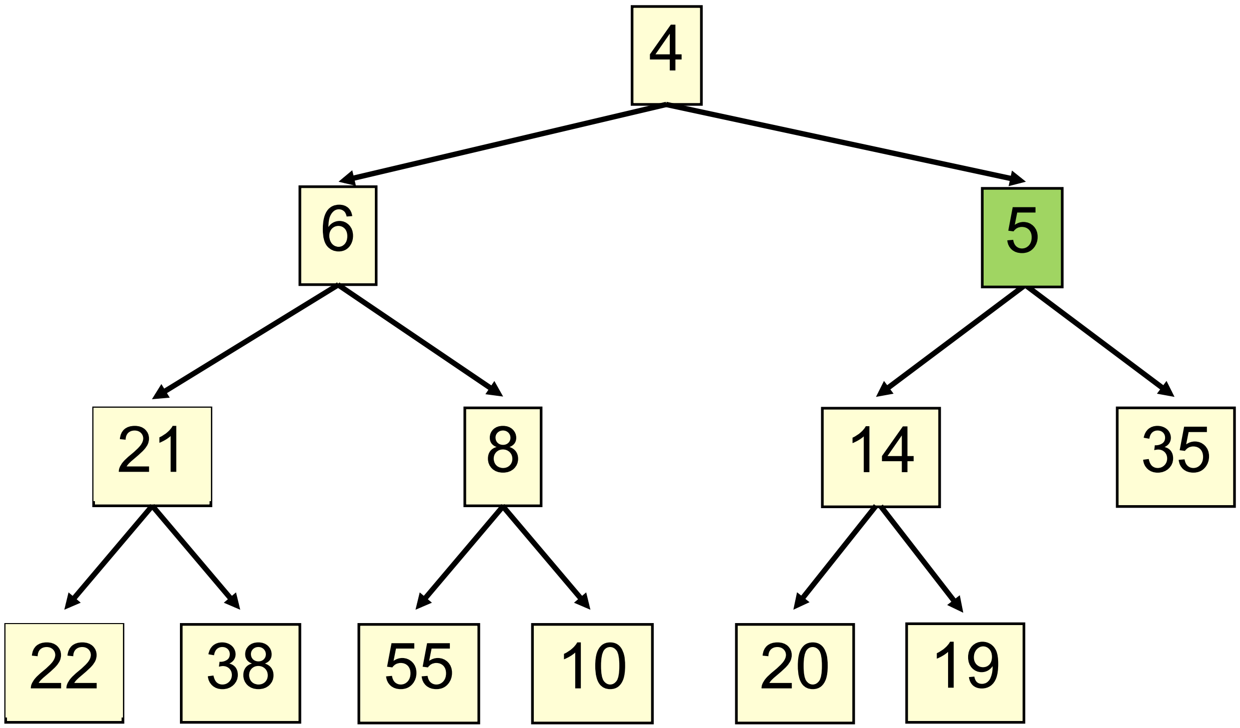
`insert()`



`insert()`



insert()



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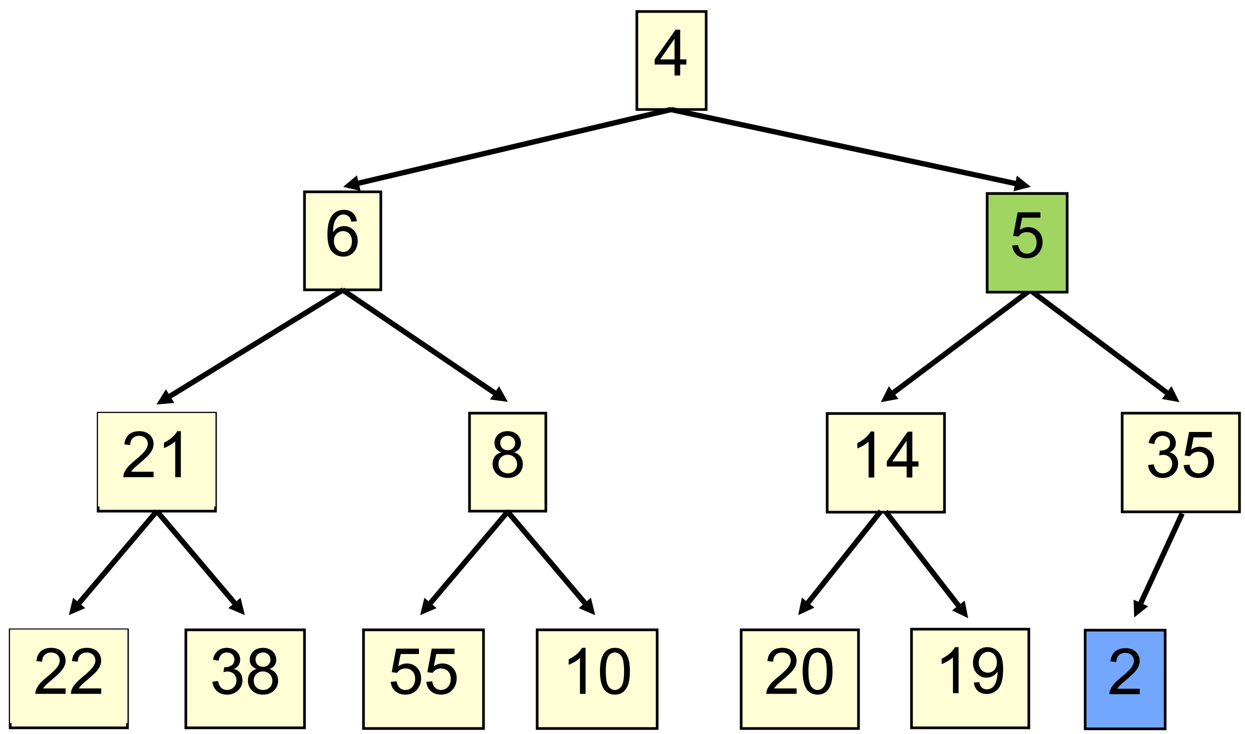
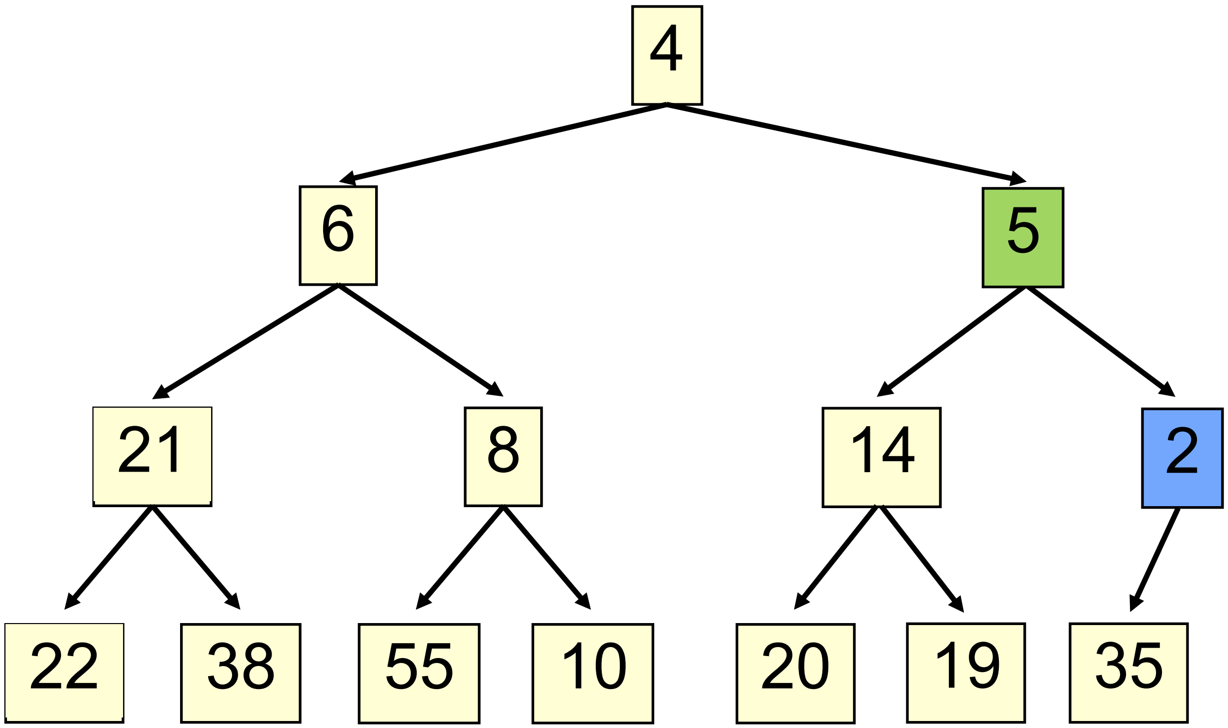
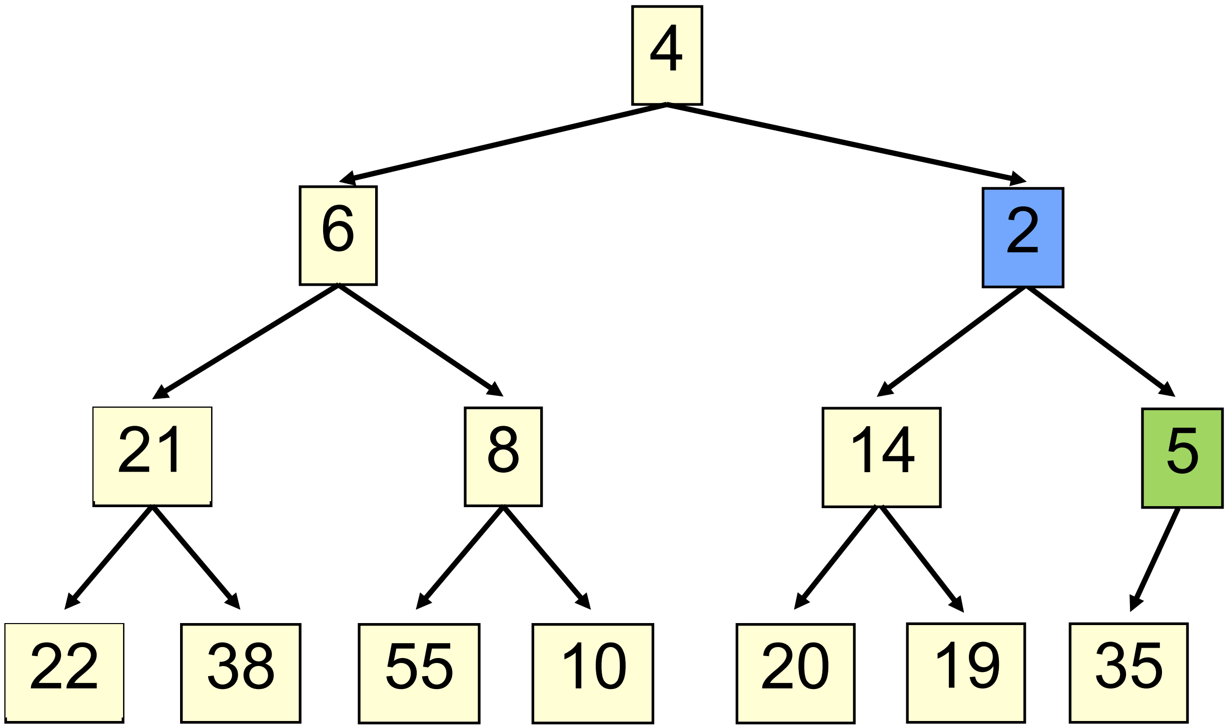


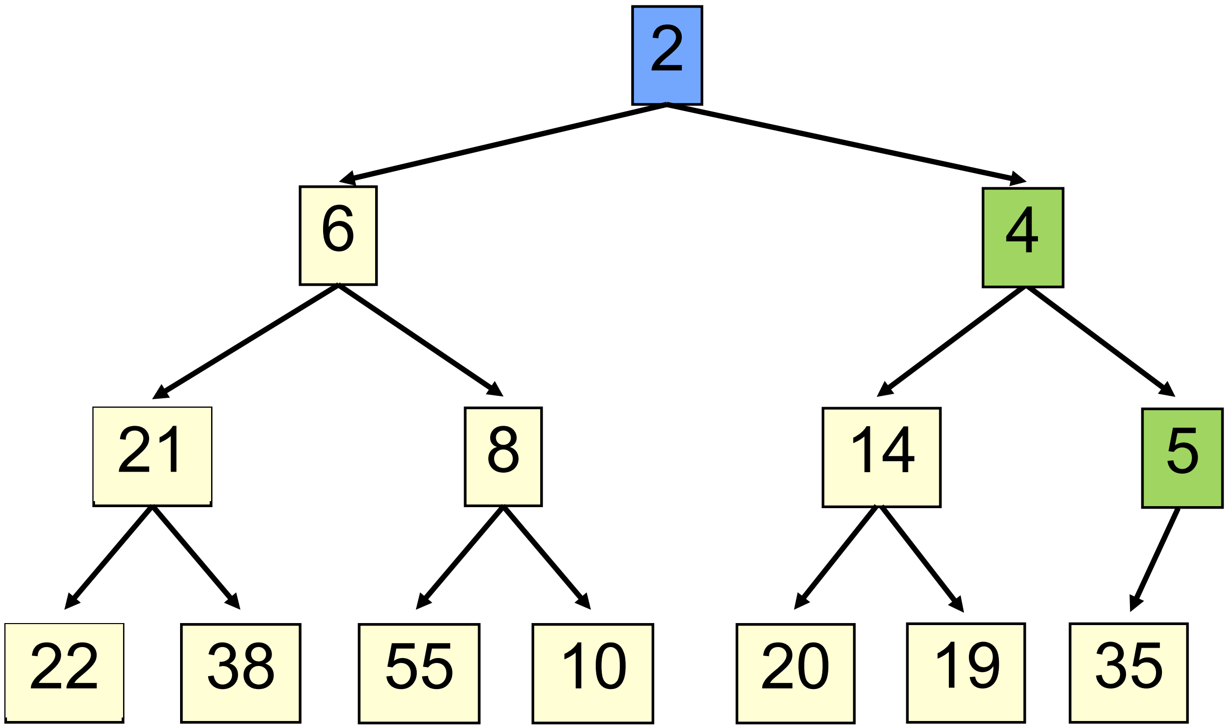
insert()



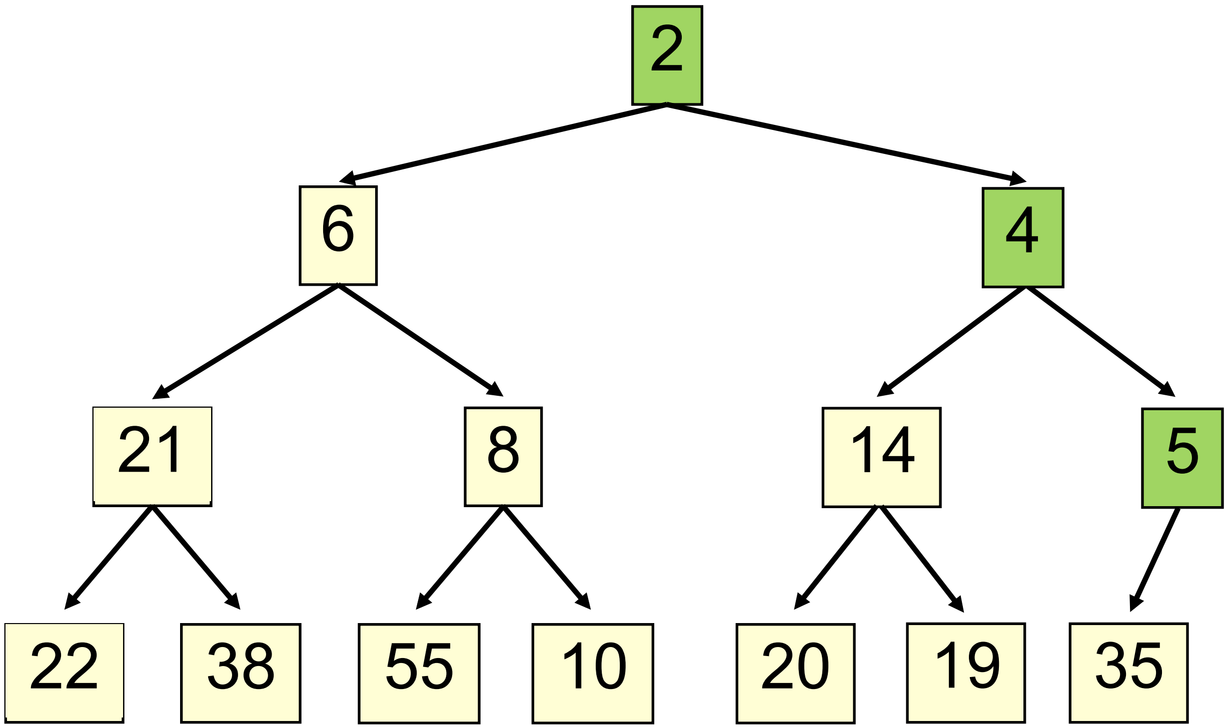
insert()



`insert()`



insert()



`insert()`

- Time is O(log n), since the tree is balanced
  - size of tree is exponential as a function of depth
  - depth of tree is logarithmic as a function of size

insert()


```
/** An instance of a priority queue */
class PriorityQueue<E> extends java.util.Vector<E> {

  /** Insert e into the priority queue */
  public void insert(E e) {
    super.add(e); //add to end of array
    bubbleUp(size() - 1); // given on next slide
  }
}
```

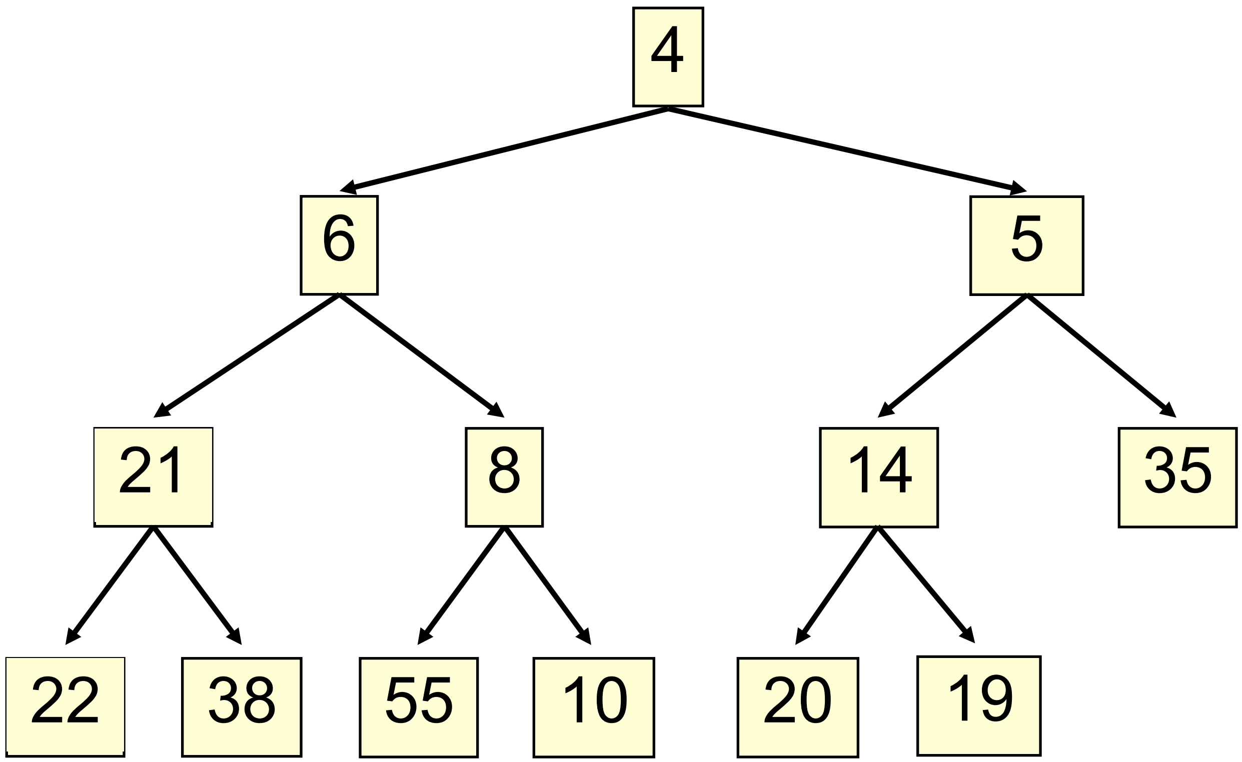
insert()


```
class PriorityQueue<E> extends java.util.Vector<E> {

 /** Bubble element k up the tree */
 private void bubbleUp(int k) {

    int p= (k-1)/2;   // p is the parent of k

    // inv: Every element satisfies the heap property
    // except element k might be smaller than its parent
    while (k>0  &&  get(k).compareTo(get(p)) < 0) {
         “swap elements k and p”;
         k= p;
         p= (k-1)/2;
    }
}
```

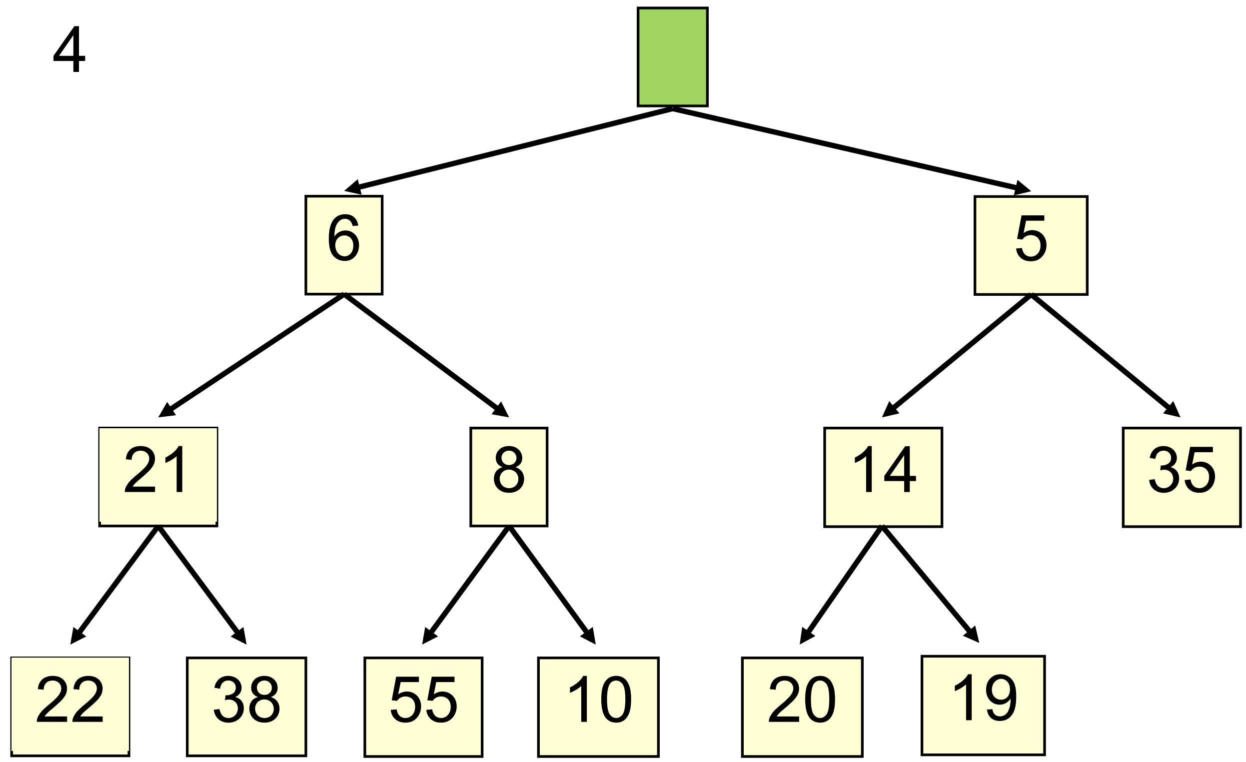
`extract()`

- Remove the least element – it is at the root
- This leaves a hole at the root – fill it in with the last element of the array
- If this violates heap order because the root element is too big, swap it down with the smaller of its children
- Continue swapping it down until it finds its rightful place
- The heap invariant is maintained!

extract()

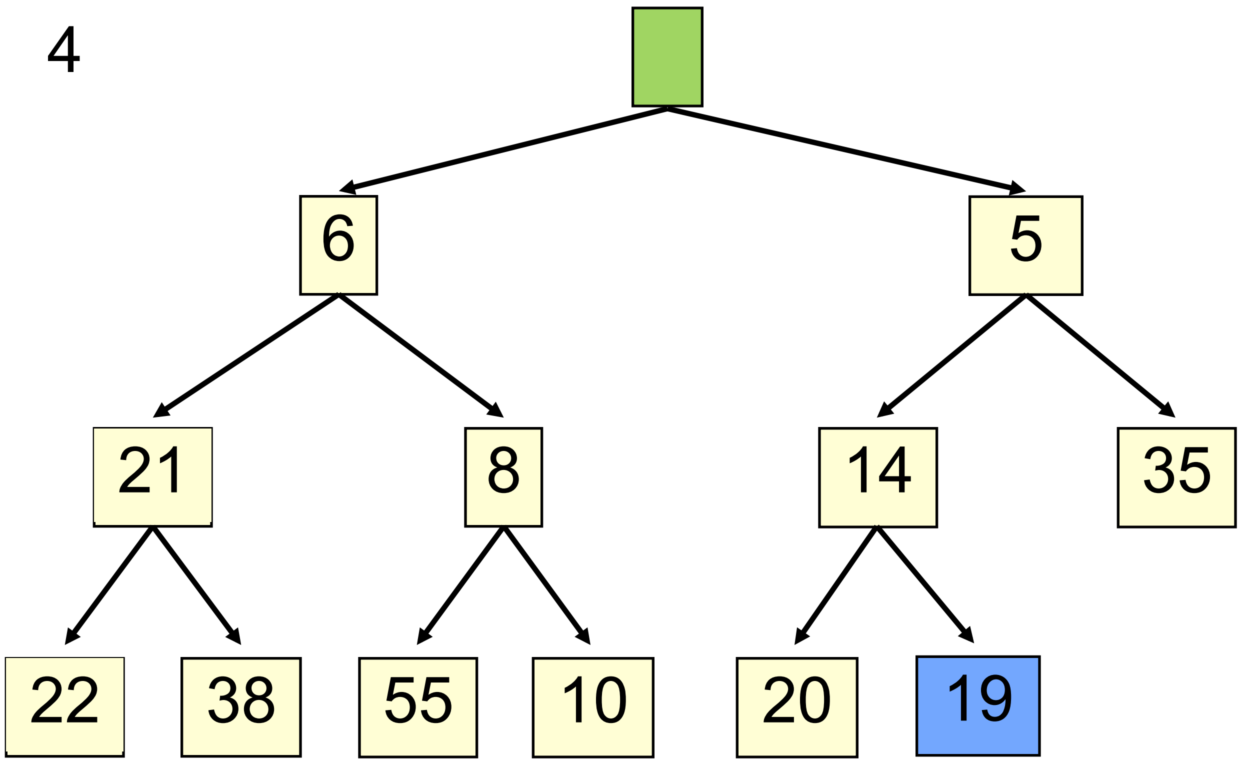


extract()



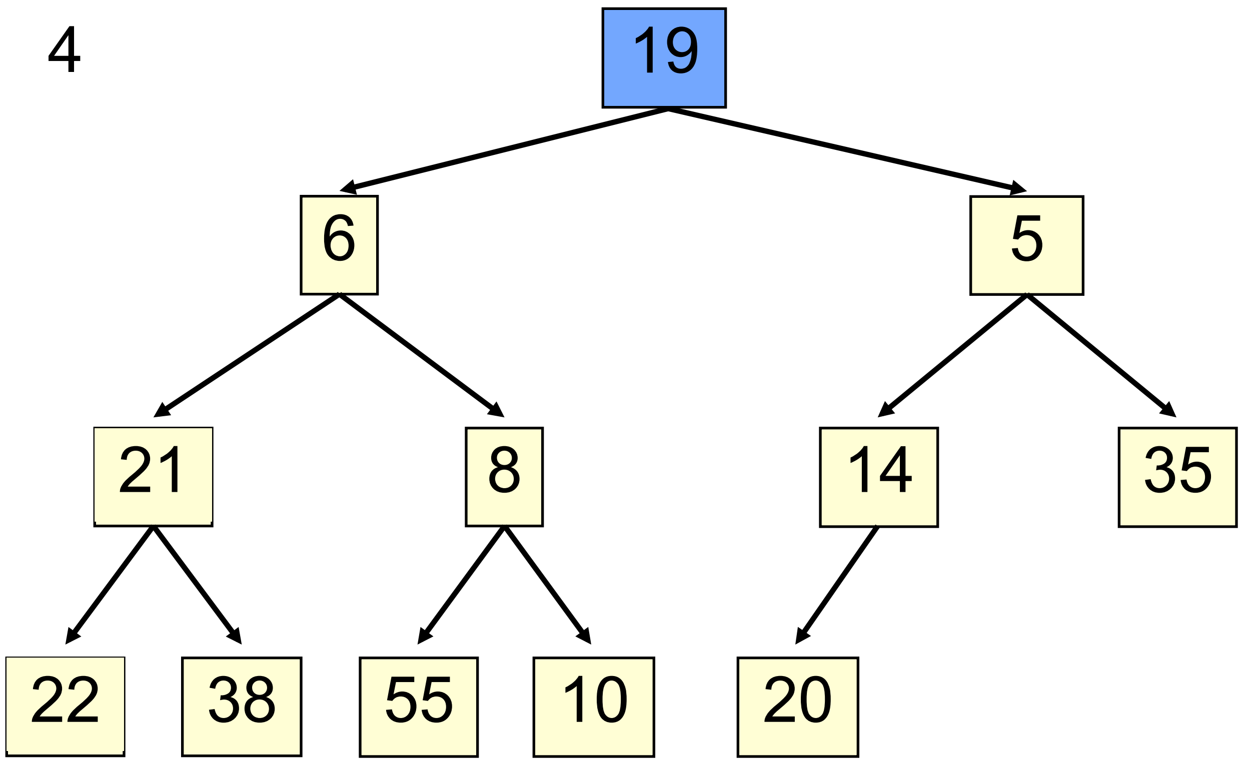
`extract()`

4



extract()

4



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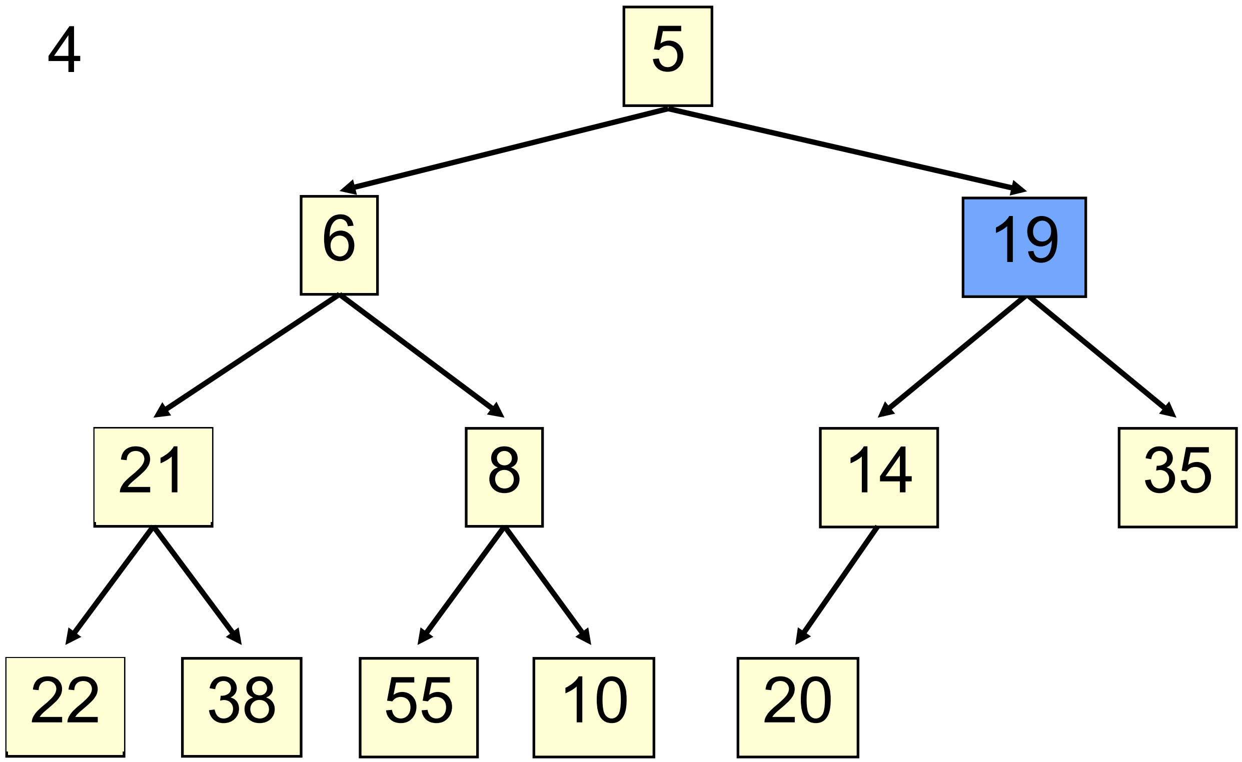
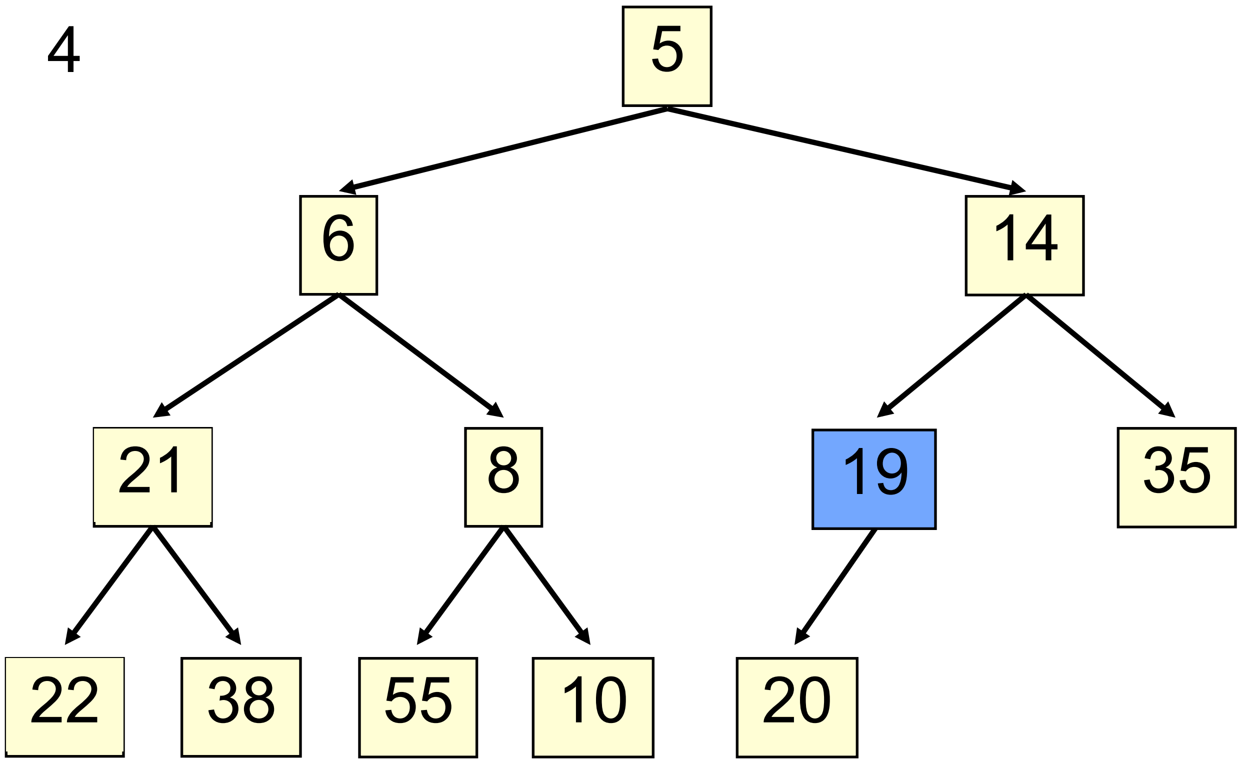


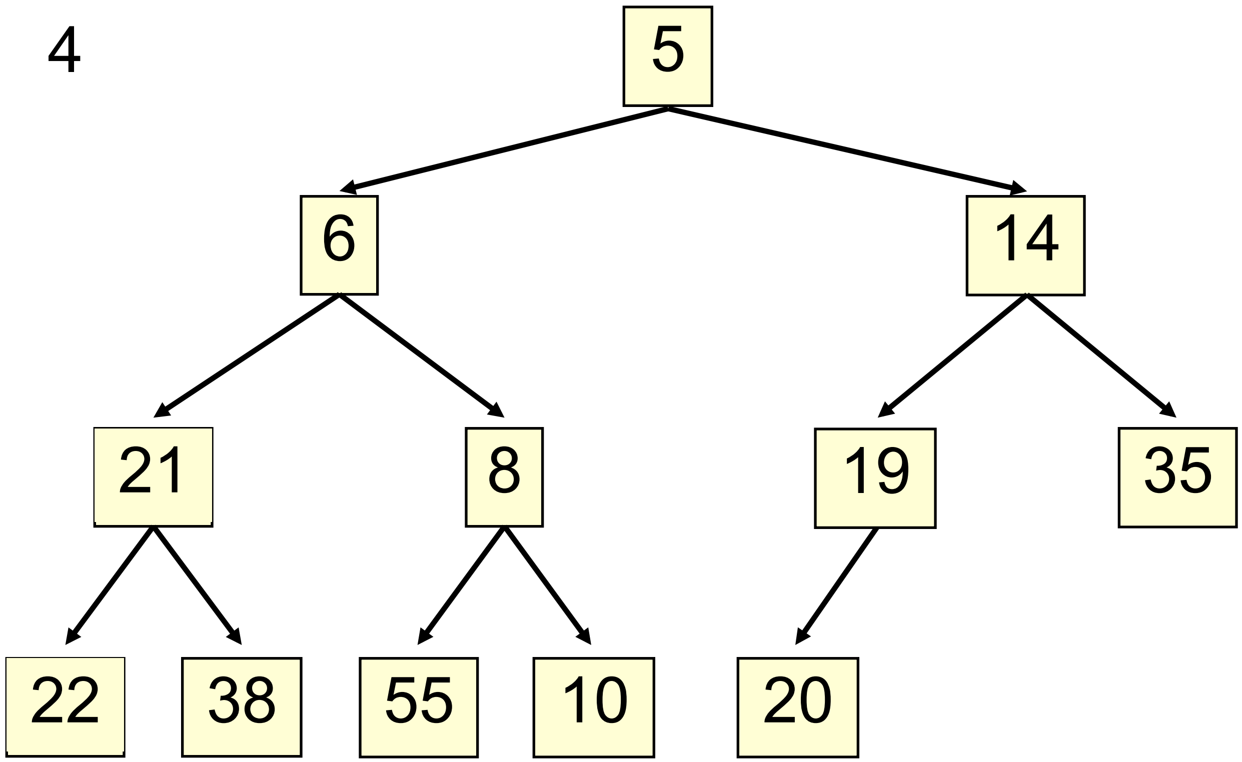
`extract()`

4



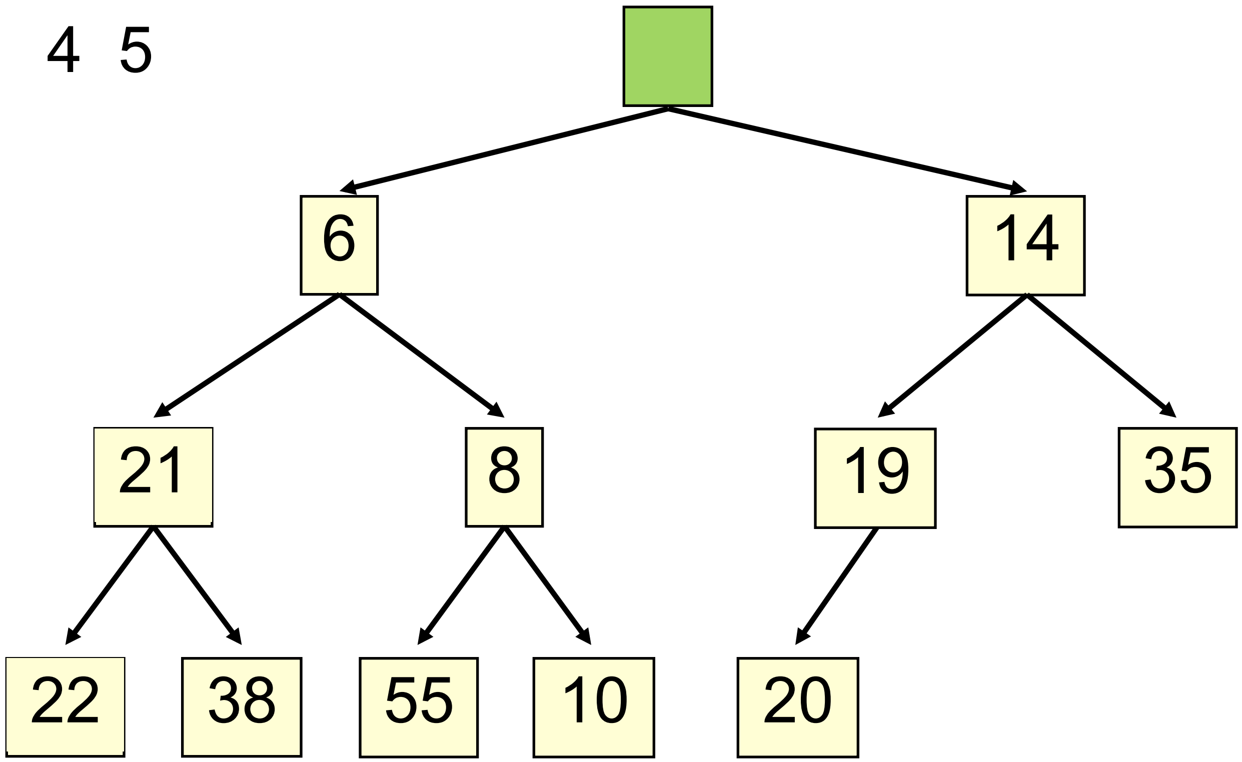
extract()

4



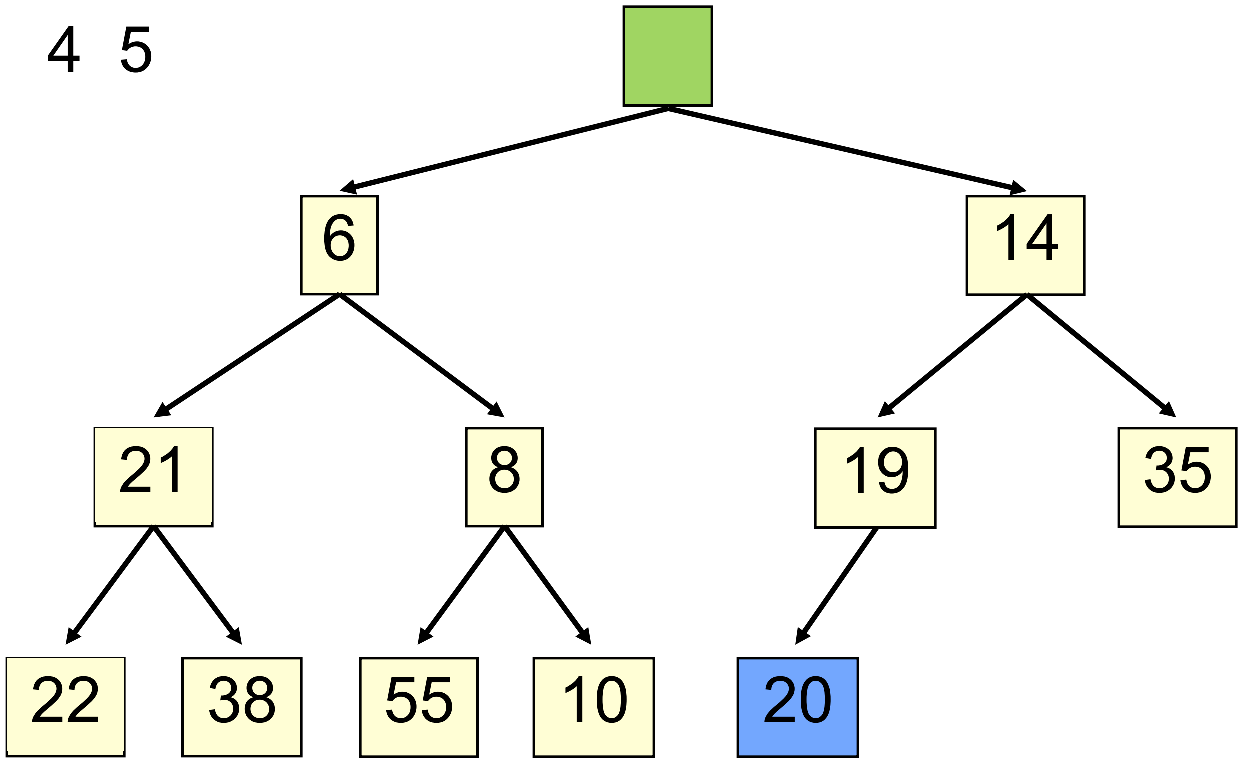
`extract()`

4 5



`extract()`

4 5



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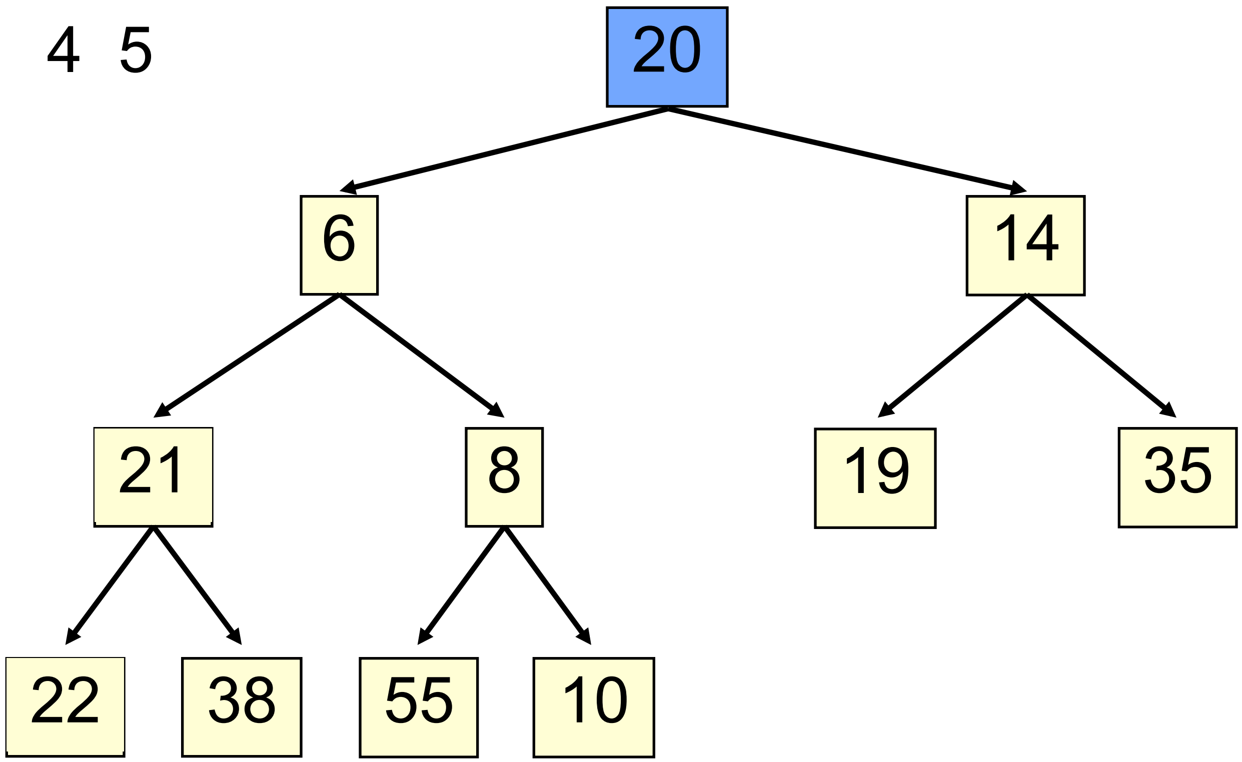
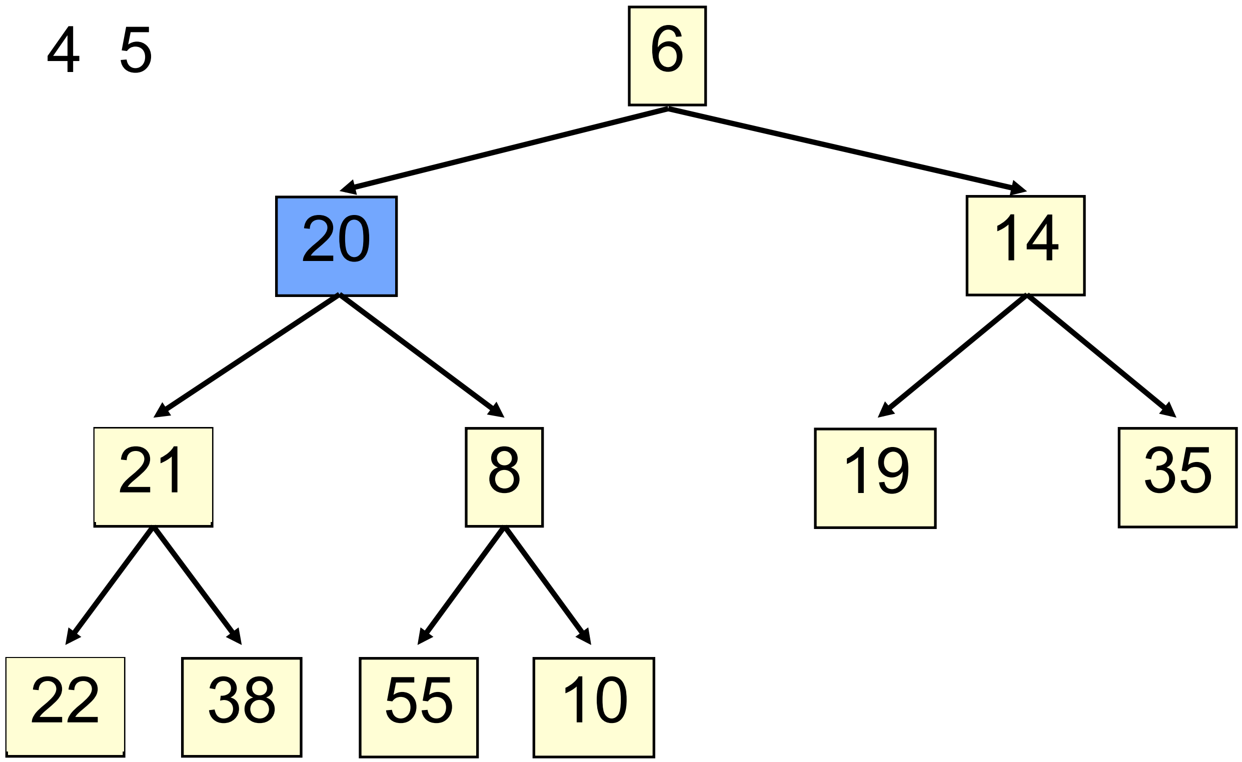


`extract()`

4 5



extract()

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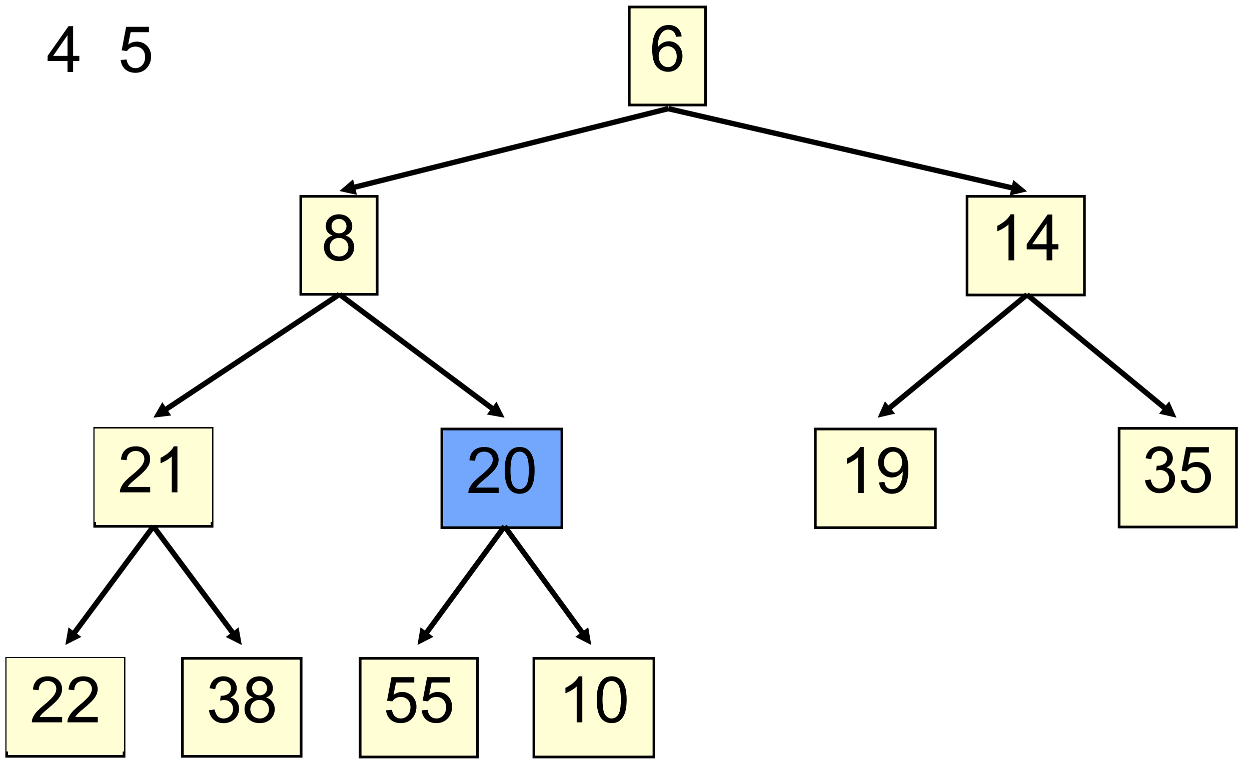
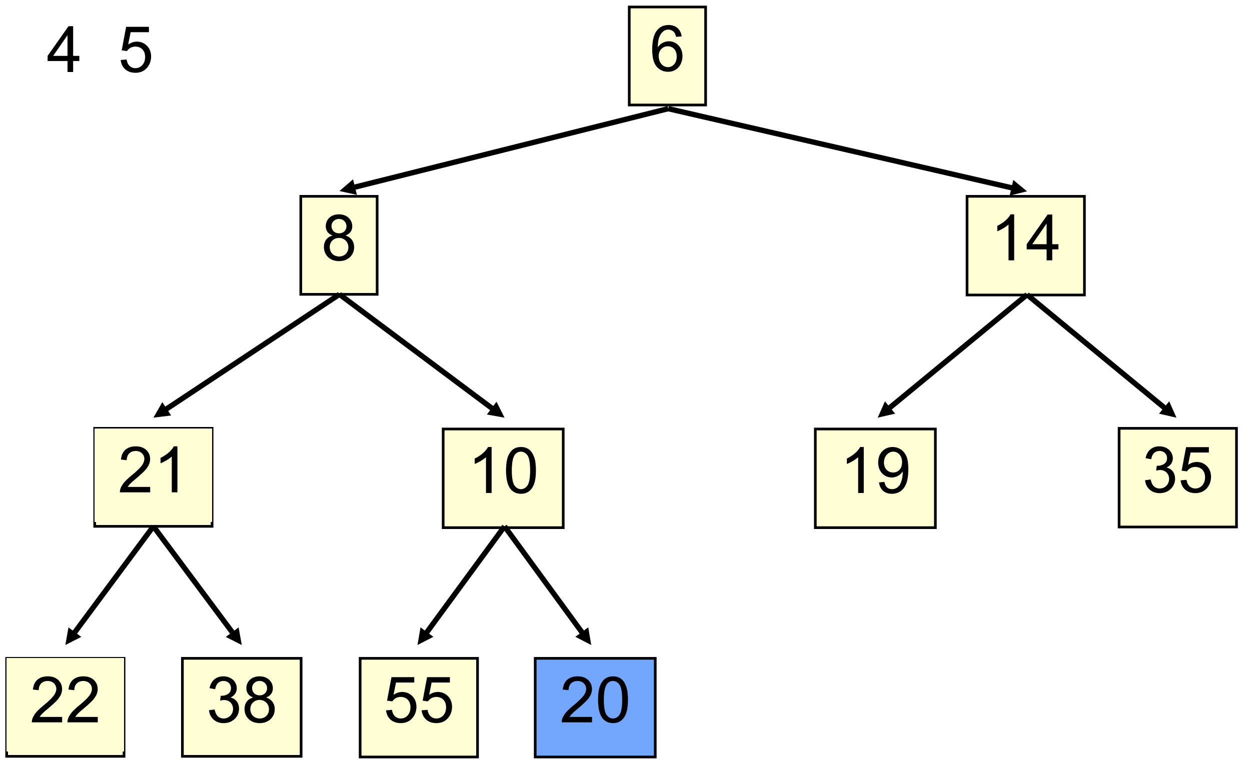


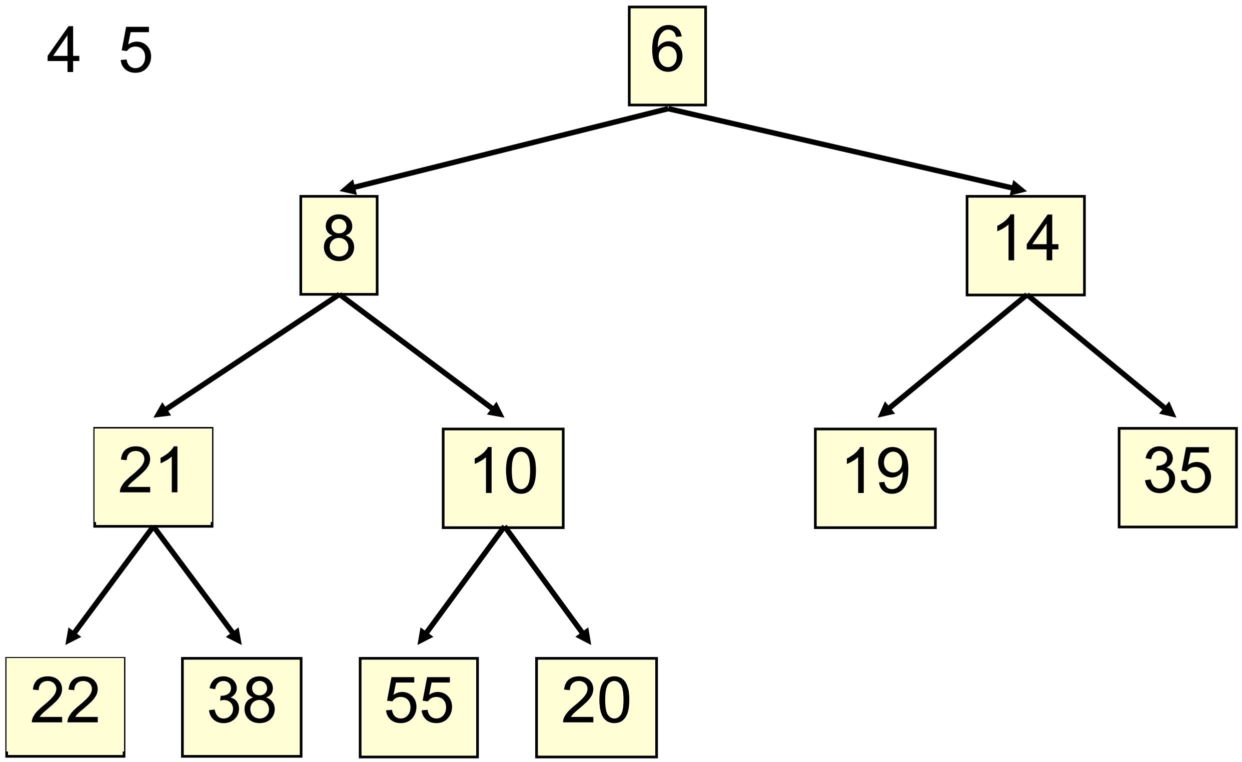
`extract()`

4 5



extract()

4 5



`extract()`

Time is O(log n), since the tree is balanced

extract()


```
/** Remove and return the smallest element
     (return null if list is empty) */
public E extract() {
    if (size() == 0) return null;
    E temp=  get(0);           // smallest value is at root
    set(0, get(size() – 1)); // move last element to root
    setSize(size() - 1);      // reduce size by 1
    bubbleDown(0);
    return temp;
}
```

```
/** Bubble the root down to its heap position.
    Pre: tree is a heap except: root may be >than a child */
private void bubbleDown() {

   int k= 0;
   // Set c to smaller of k's children
   int c= 2*k + 2;      // k's right child
   if (c > size()-1 || get(c-1).compareTo(get(c)) < 0)  c--;

   // inv tree is a heap except: element k may be > than a child.
   //        Also k's smallest child is element c
   while (c < size()  &&  get(k).compareTo(get(c) > 0) {
      Swap elements at k and c;
      k= c;
      c= 2*k + 2;      // k's right child
      if (c > size()-1 || get(c-1).compareTo(get(c)) < 0)  c--;
   }
}
```

HeapSort

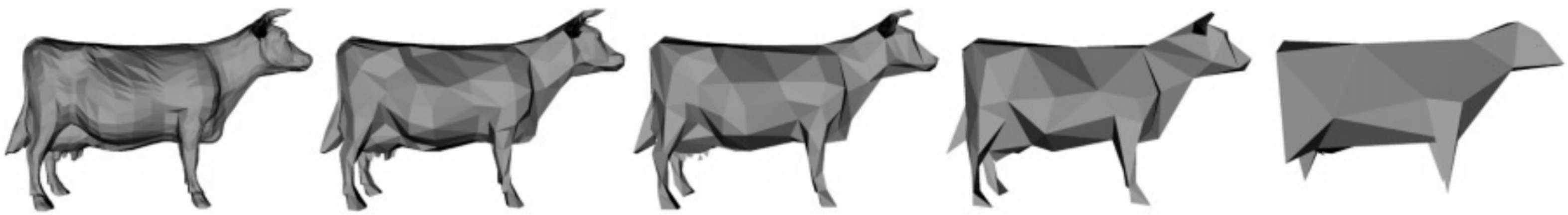
Given a **`Comparable[]`** array of length n,

- Put all n elements into a heap – O(n log n)
- Repeatedly get the min – O(n log n)

```
public static void heapSort(Comparable[] b)
{
   PriorityQueue<Comparable> pq=
        new PriorityQueue<Comparable>(b);
    for (int i = 0; i < b.length; i++) {
        b[i] = pq.extract();
    }
}
```

One can do the two stages in the array itself, in place, so algorithm takes O(1) space.

Many uses of priority queues & heaps



Surface simplification [Garland and Heckbert 1997]

- Mesh compression: quadric error mesh simplification
- Event-driven simulation: customers in a line
- Collision detection: "next time of contact" for colliding bodies
- Data compression: Huffman coding
- Graph searching: Dijkstra's algorithm, Prim's algorithm
- AI Path Planning: A* search
- Statistics: maintain largest M values in a sequence
- Operating systems: load balancing, interrupt handling
- Discrete optimization: bin packing, scheduling
- Spam filtering: Bayesian spam filter