

heap

- complete binary tree (review)
- heap and priority queues (Chapter 9)
- binary heap and min-heap
- max-heap demo
- *max-heap coding*
- heap sort (Chapter 7)

heap coding: heap.h

Heap ADT: A **one - based** and **one dimensional array** is used to simplify parent and child calculations.

```
struct Heap {
    int *nodes;          // an array of nodes
    int capacity;        // array size of node or key, item
    int N;               // the number of nodes in the heap
    bool (*comp)(Heap*, int, int);
    Heap(int capa = 2) {
        capacity = capa;
        nodes = new int[capacity];
        N = 0;
        comp = nullptr;
    };
    ~Heap() {};
};
using heap = Heap*;
```

heap coding: heap.h

```
void clear(heap hp);           // deallocate heap
int size(heap hp);            // return nodes in heap currently
int level(int n);             // return level based on num of nodes
int capacity(heap hp);        // return its capacity (array size)
int reserve(heap hp, int capa); // reserve the array size (= capacity)
int full(heap hp);            // return true/false
int empty(heap hp);           // return true/false
void grow(heap hp, int key);  // add a new key
void trim(heap hp);          // delete a queue
int heapify(heap hp);          // convert a complete BT into a heap

// helper functions to support grow/trim functions
int less(heap hp, int i, int j); // used in max heap
int more(heap hp, int i, int j); // used in min heap
void swim(heap hp, int k);      // bubble up
void sink(heap hp, int k);      // tickle down
// helper functions to check heap invariant
int heapOrdered(heap hp);       // is heap[1..N] a heap?
```

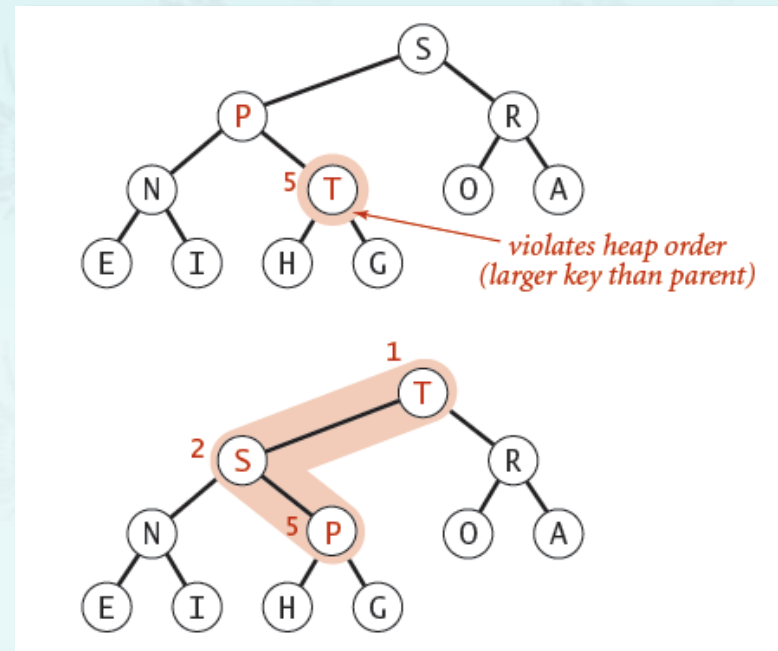
heap coding

Promotion in a heap: swim

- To eliminate the violation:
 - Swap key in child with key in parent.
 - Repeat until **heap order** restored.

swim up
or
sink down

This is a maxheap example.



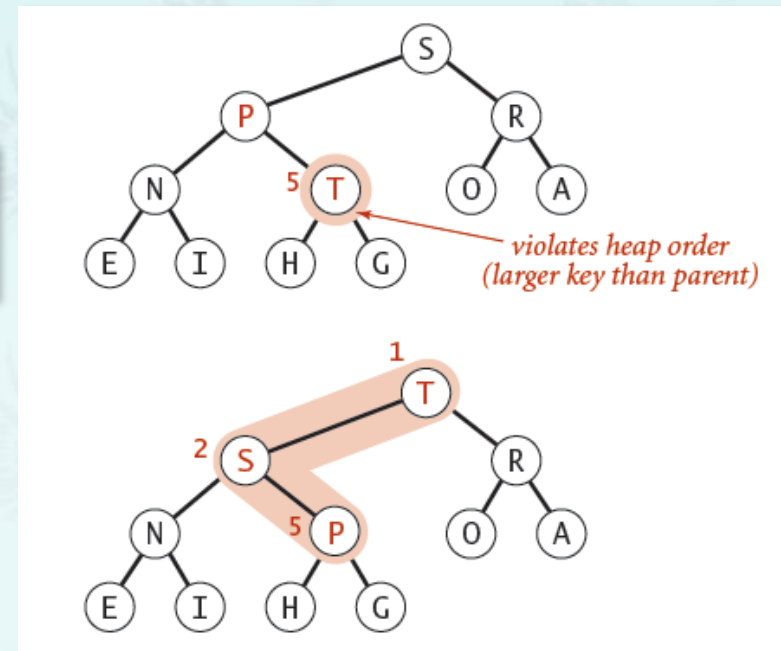
heap coding

Promotion in a heap: swim

- To eliminate the violation:
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 - Repeat until heap order restored.

guess a name?

```
bool     (heap h, int p, int c) {  
    return h->nodes[p] < h->nodes[c];  
}
```



heap coding

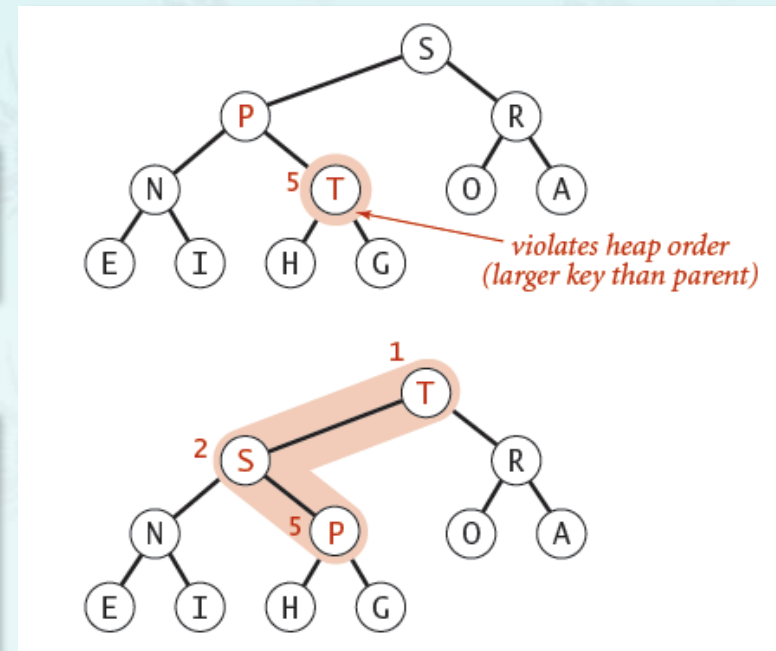
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}
```

```
void     (heap h, int p, int c) {  
    int item = h->nodes[p];  
    h->nodes[p] = h->nodes[c];  
    h->nodes[c] = item;  
}
```



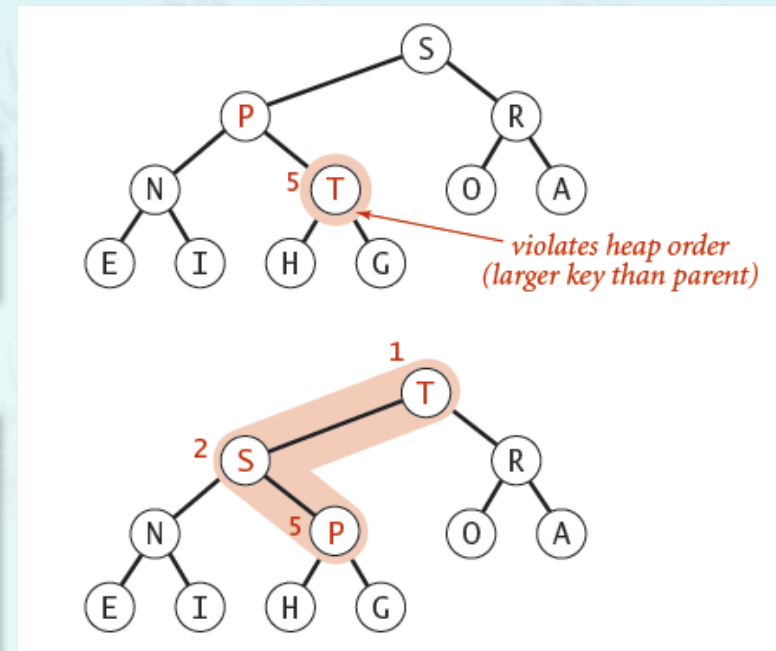
heap coding

Promotion in a heap: swim

- To eliminate the violation:
 - Swap key in child with key in parent.
 - Repeat until heap order restored.

```
bool less(heap h, int p, int c) {  
    return h->nodes[p] < h->nodes[c];  
}
```

```
void swap(heap h, int p, int c) {  
    int item = h->nodes[p];  
    h->nodes[p] = h->nodes[c];  
    h->nodes[c] = item;  
}
```



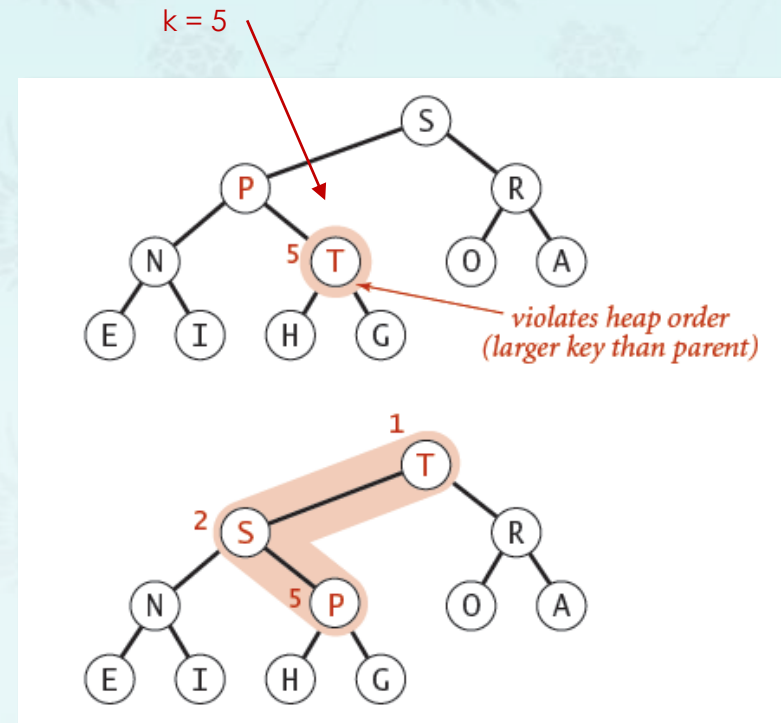
heap coding

Promotion in a heap: swim

- To eliminate the violation:
 - Swap key in child with key in parent.
 - Repeat until heap order restored.

guess a name?

```
void         (heap h, int k)
{
    while (not reached at root &&
           k's parent key < k's key)
    {
        
    }
}
```

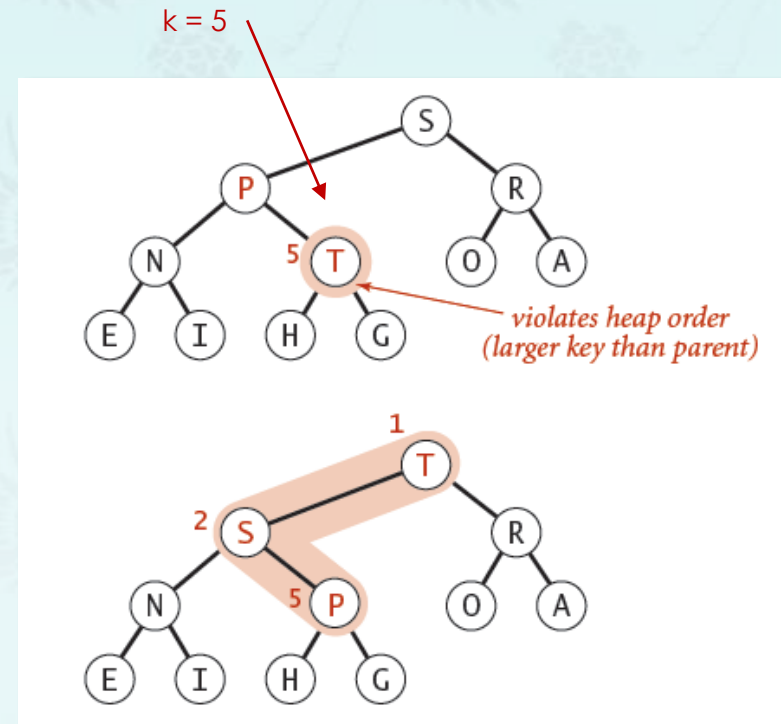


heap coding

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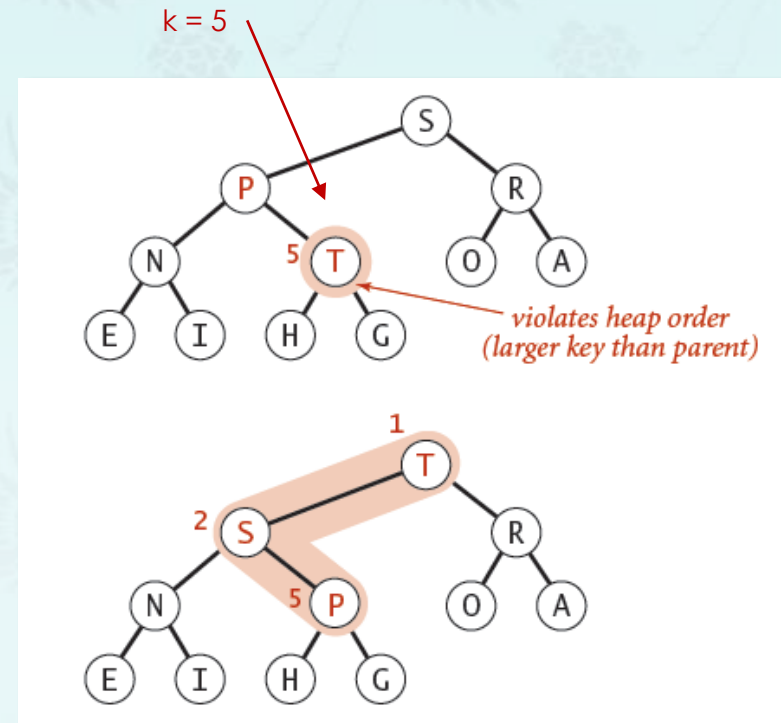


heap coding

Promotion in a heap: swim

- To eliminate the violation:
 - Swap key in child with key in parent.
 - Repeat until heap order restored.

```
void swim(heap h, int k)
{
    while (not reached at root &&
           k's parent key < k's key)
    {
        swap k and its parent
        go for the next
    }
}
```



heap coding

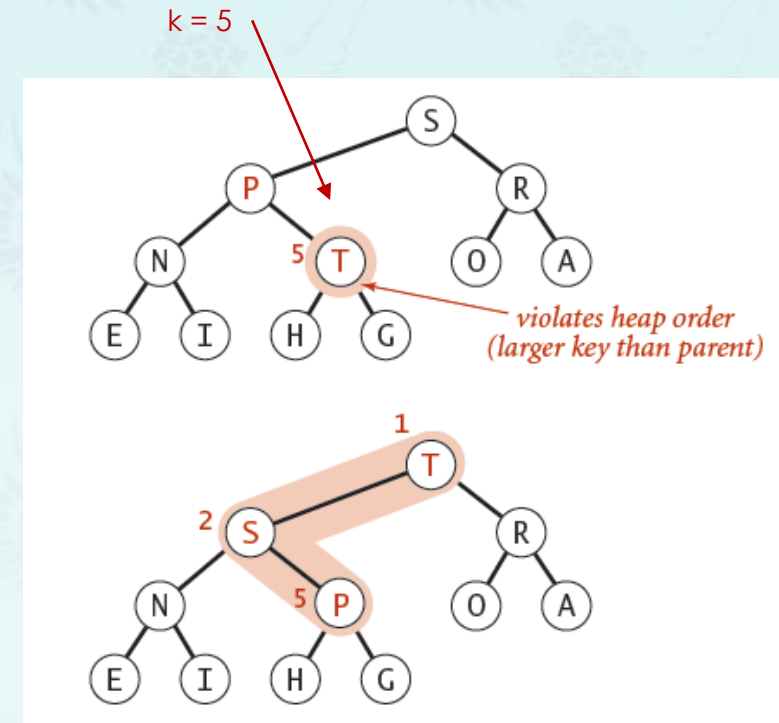
Promotion in a heap: swim

- To eliminate the violation:
 - Swap key in child with key in parent.
 - Repeat until heap order restored.

```
void swim(heap h, int k)
{
    while (k > 1 && h[k] < h[k/2])
    {
        swap(h[k], h[k/2]);
        k = k/2;
    }
}
```

not reached at root

parent of k



heap coding

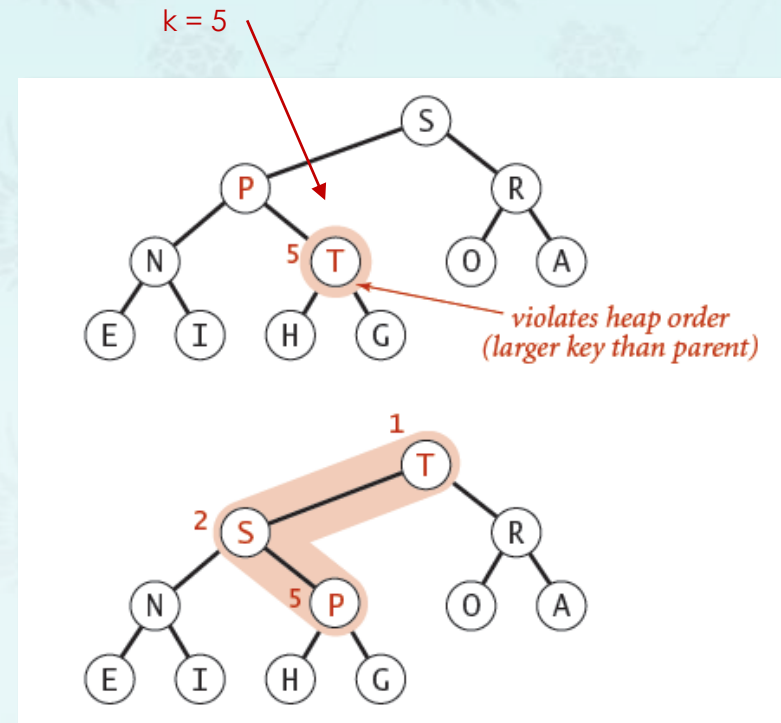
Promotion in a heap: swim

- To eliminate the violation:
 - Swap key in child with key in parent.
 - Repeat until heap order restored.

```
void swim(heap h, int k)
{
    while (k > 1 &&         )
    {
                
    }
}
```

not reached at root

parent(k/2) is less than its child(k)



heap coding

Promotion in a heap: swim

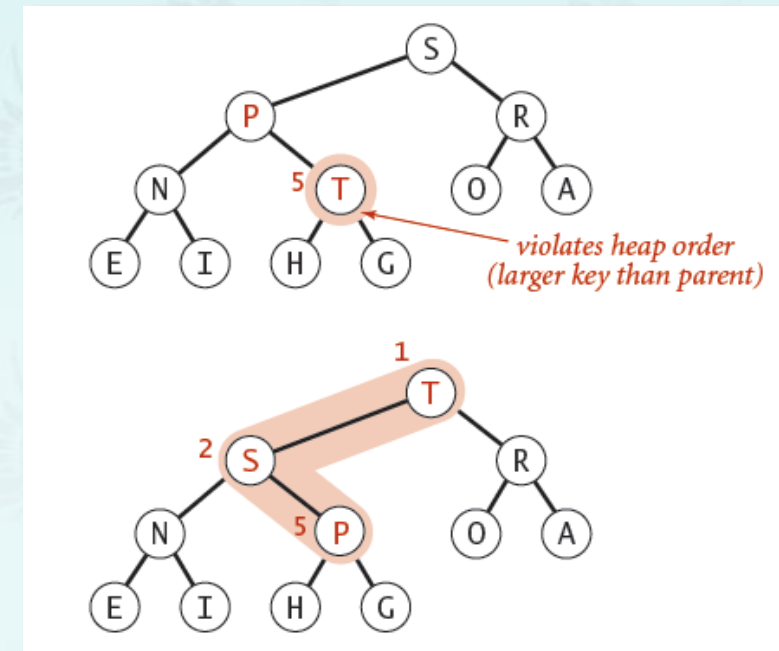
- To eliminate the violation:
 - Swap key in child with key in parent.
 - Repeat until heap order restored.

```
void swim(heap h, int k)
{
    while (k > 1 && less(h, k / 2, k))
    {
                
        swap parent(k/2)
        and its child(k)
    }
}
```

not reached at root

parent(k/2) is less its child(k)

swap parent(k/2) and its child(k)



heap coding

Promotion in a heap: swim

- To eliminate the violation:
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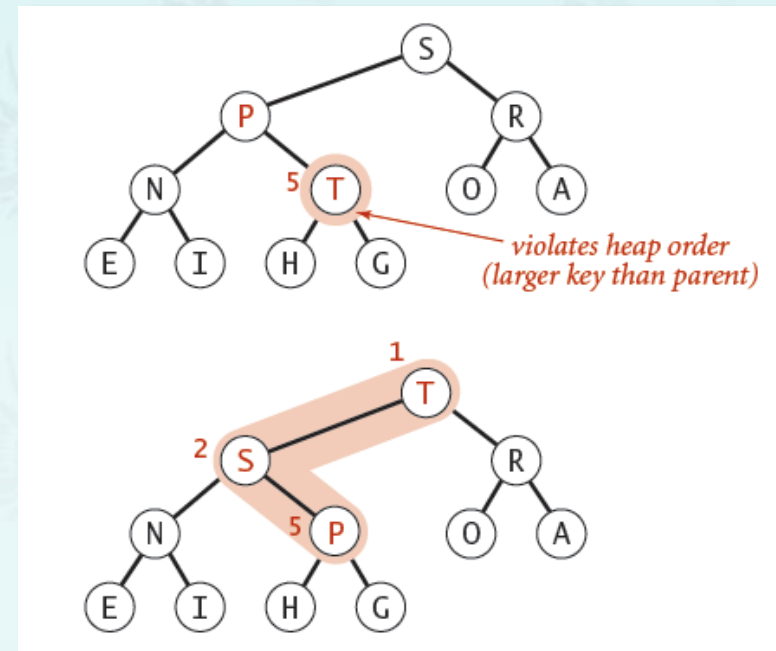
```
void swim(heap h, int k)
{
    while (k > 1 && less(h, k / 2, k))
    {
        swap(h, k / 2, k);
    }
}
```

not reached at root

parent(k/2) is less its child(k)

swap parent(k/2) and its child(k)

move up one level



heap coding

Promotion in a heap: swim

- To eliminate the violation:
 - Swap key in child with key in parent.
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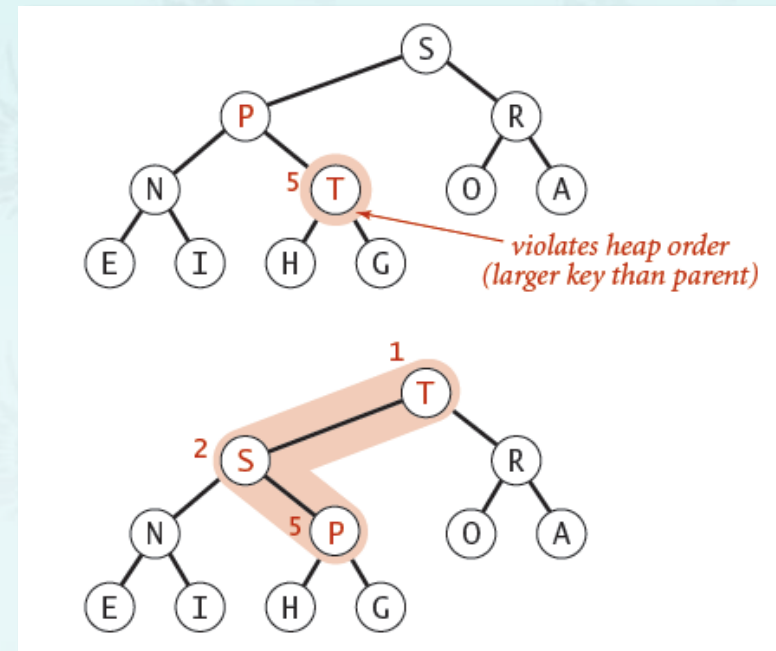
```
void swim(heap h, int k)
{
    while (k > 1 && less(h, k / 2, k))
    {
        swap(h, k / 2, k);
        k = k / 2;
    }
}
```

not reached at root

parent(k/2) is less its child(k)

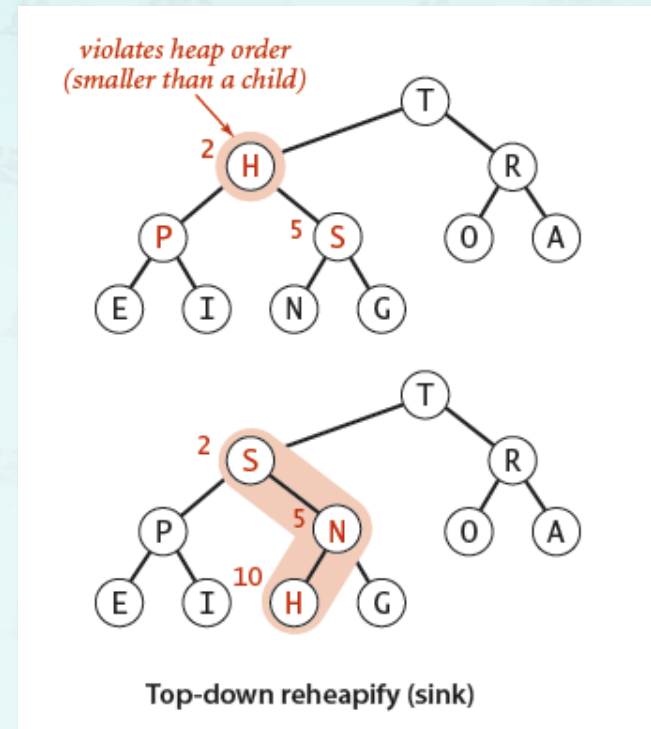
swap parent(k/2) and its child(k)

move up one level



heap coding

swim up
or
sink down



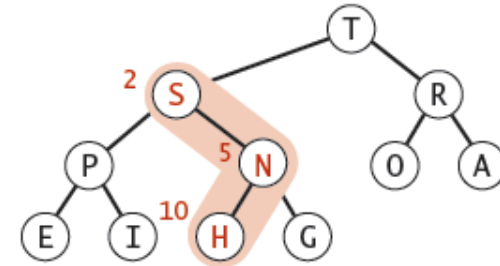
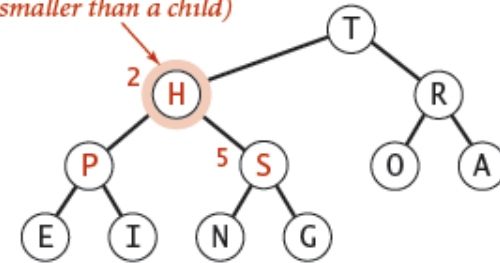
heap coding

Demotion in a heap: sink

- Parent's key becomes **smaller** than one (or both) of its children's.
- To eliminate the violation:
 - Swap key in parent with key in **larger** child (of two)
 - Repeat until heap order restored.

Why not smaller child?

violates heap order
(smaller than a child)



Top-down reheapify (sink)

This is a maxheap example.

heap coding

Demotion in a heap: sink

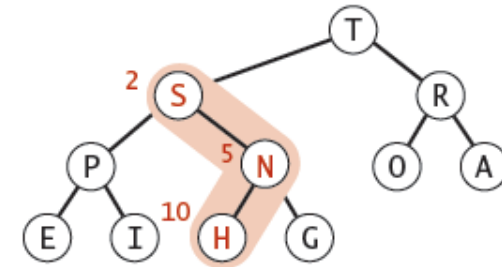
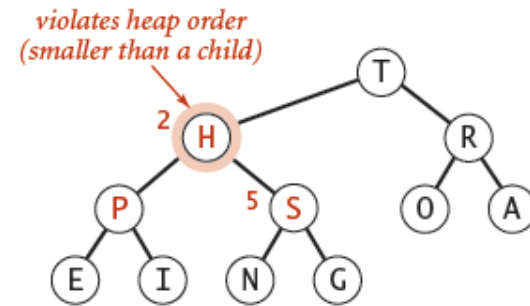
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 - Swap key in parent with key in **larger** child (of two)
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Why not smaller child?

```
void sink(heap h, int k)
{
    while (k's child not reached the last)
    {
        find the larger child of k, let it be j. (j = 5)

        if k's key is not less than j's key, break;
        swap k and j since k's key > j's key
        set k to the next node wh
    }
}
```

k = 2



Top-down reheapify (sink)

heap coding

Demotion in a heap: sink

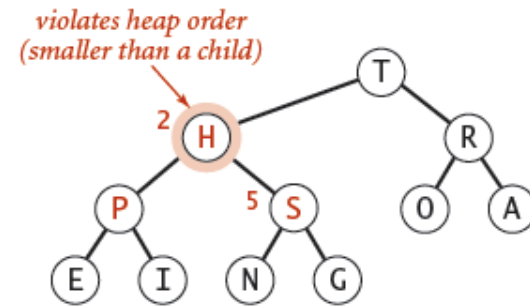
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        swap k and j since k's key > j's key
        set k to the next node which is j.
    }
}
```

k = 2



Top-down reheapify (sink)

heap coding

Demotion in a heap: sink

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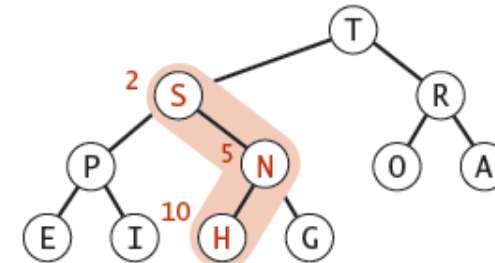
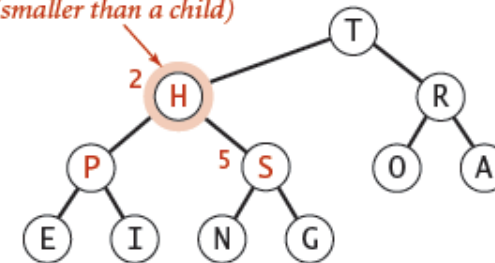
```
    while (k's child not reached the last)
```

```
    {
```

```
        find the larger child of k, let it be j. (j = 5)
```

```
    }
```

violates heap order
(smaller than a child)



Top-down reheapify (sink)

heap coding

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Why not smaller child?

```
void sink(heap h, int k)
```

```
{
```

```
  while (2 * k <= h->N)
```

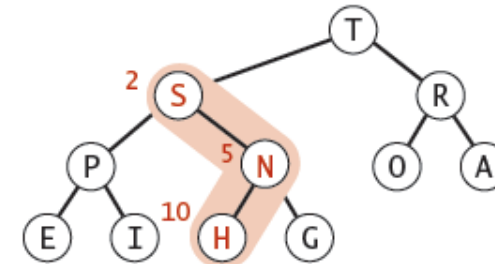
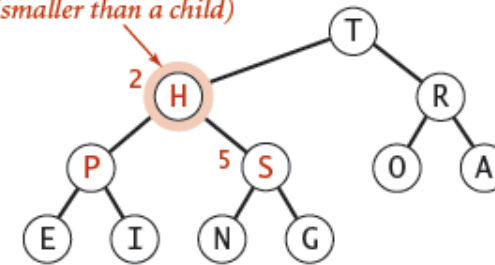
```
  {
```

```
    find the larger child of k, let it be j. (j = 5)
```

```
  }
```

children of node **k**
are **2k** and **2k+1**

violates heap order
(smaller than a child)



Top-down reheapify (sink)

heap coding

Demotion in a heap: sink

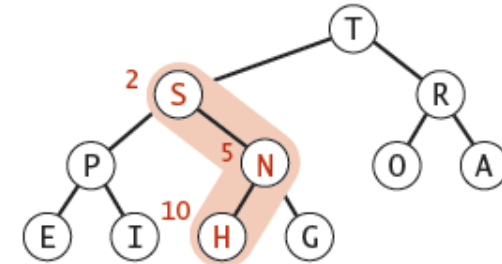
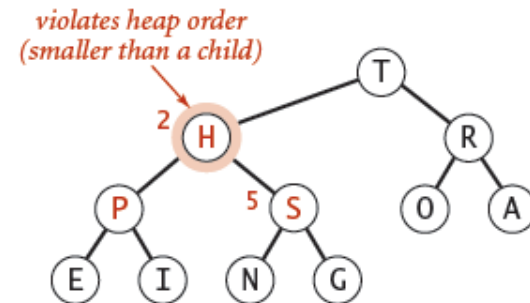
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```

```
{
  while (2 * k <= h->N)
  {
    int j = 2 * k;
```

children of node k
are $2k$ and $2k+1$

find the larger child of k , let it be j . ($j = 5$)



Top-down reheapify (sink)

heap coding

Demotion in a heap: sink

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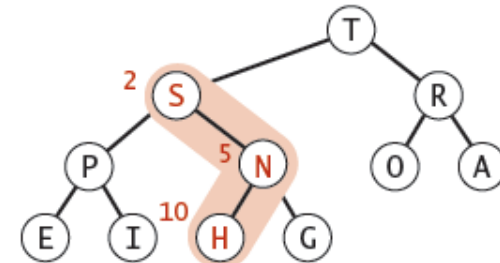
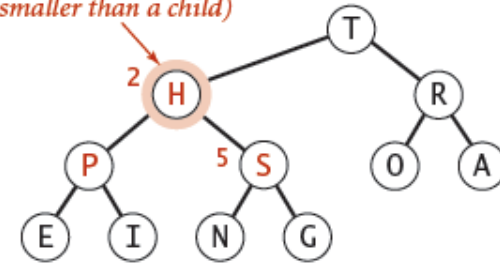
```
    int j = 2 * k;
```

```
    if (j < h->N && less(h, j, j + 1)) j++;
```

```
  }
```

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Top-down reheapify (sink)

heap coding

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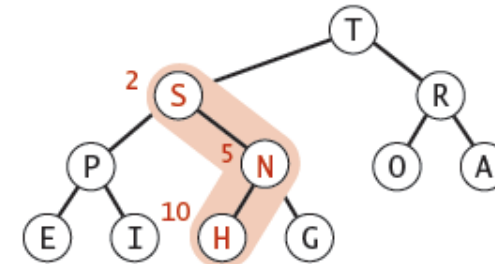
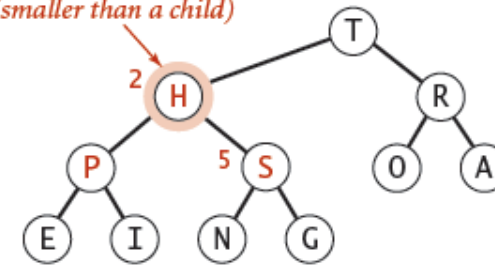
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```
    if (j < h->N && less(h, j, j + 1)) j++;
```

if k's key is not less than j's key, break;
swap k and j since k's key > j's key
set k to the next node (which is j.)

```
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violates heap order
(smaller than a child)



Top-down reheapify (sink)

heap coding

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```

```
{
```

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```

```
  {
```

```
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```

```
    if (j < h->N && less(h, j, j + 1)) j++;
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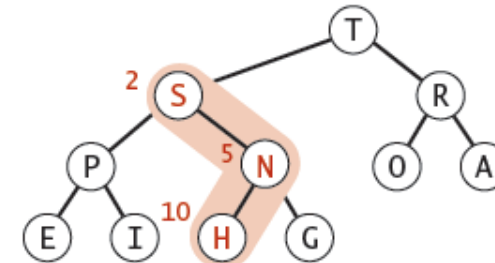
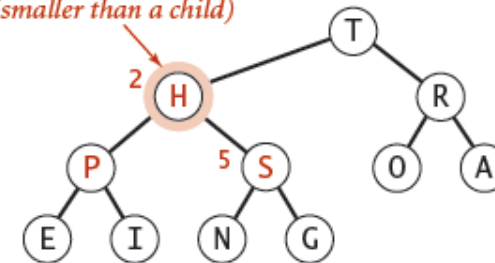
```
    if (!less(h, k, j)) break;
```

```
    swap k and j since k's key > j's key  
    set k to the next node (which is j.)
```

```
}
```

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(smaller than a child)



Top-down reheapify (sink)

heap coding

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```

```
{
```

```
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```

```
  {
```

```
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```

```
    if (j < h->N && less(h, j, j + 1)) j++;
```

```
    if (!less(h, k, j)) break;
```

```
    swap(h, k, j);
```

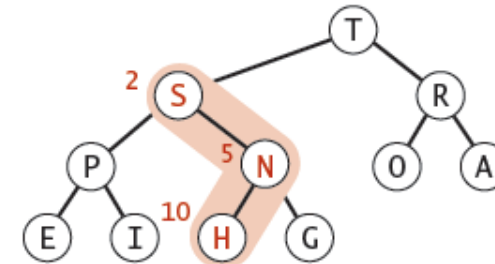
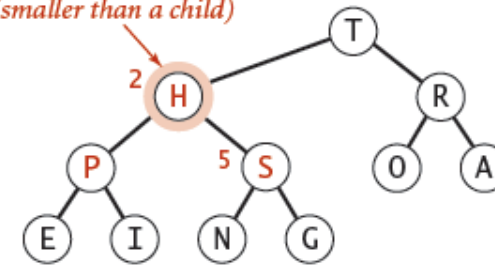
```
    set k to the next node (which is j.)
```

```
  }
```

```
}
```

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are **2k** and **2k+1**

violates heap order
(smaller than a child)



Top-down reheapify (sink)

heap coding

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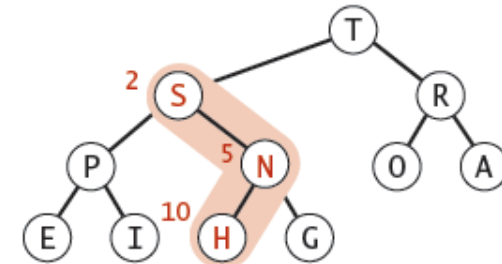
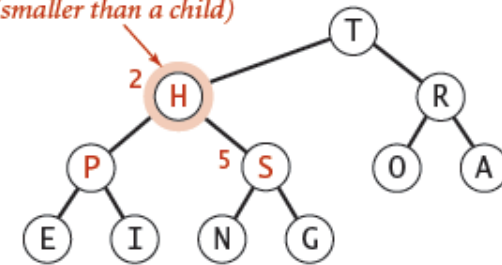
Why not smaller child?

```
void sink(heap h, int k)
{
    while (2 * k <= h->N)
    {
        int j = 2 * k;

        if (j < h->N && less(h, j, j + 1)) j++;
        if (!less(h, k, j)) break;
        swap(h, k, j);
        k = j;
    }
}
```

children of node **k**
are **2k** and **2k+1**

violates heap order
(smaller than a child)



Top-down reheapify (sink)

heap coding

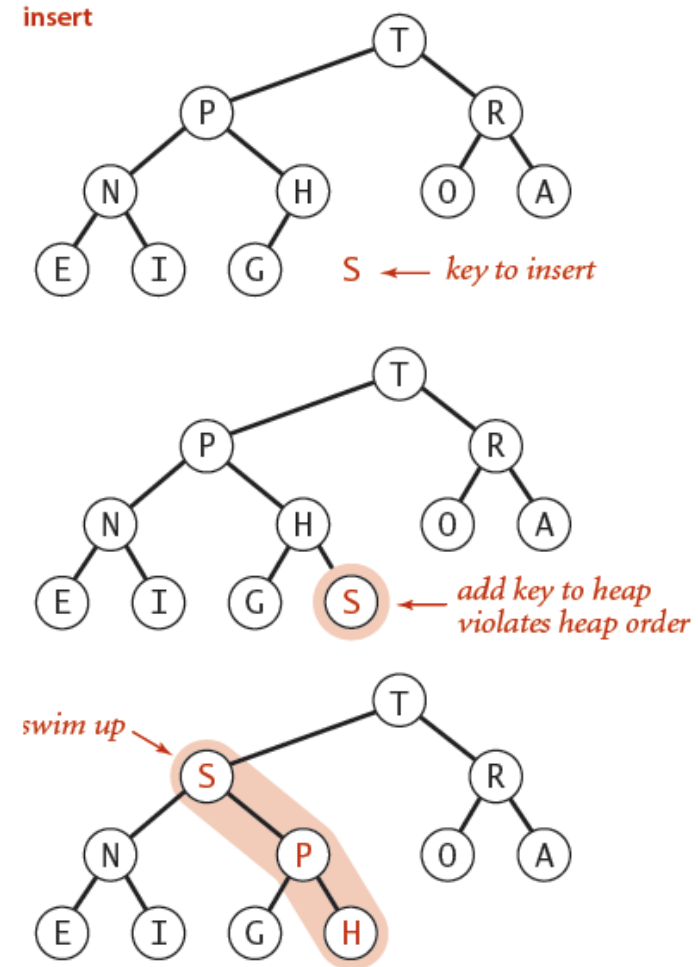
- Insert: Add node at end, then **swim** it up.
 - Cost: At most $1 + \log N$ compares.

Insert

What is N now?

Step 1

Step 2



heap coding

Insertion in a heap:

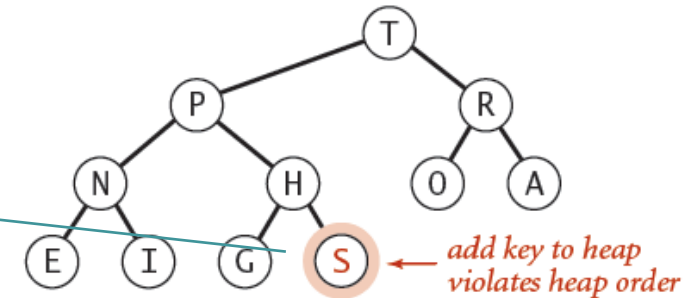
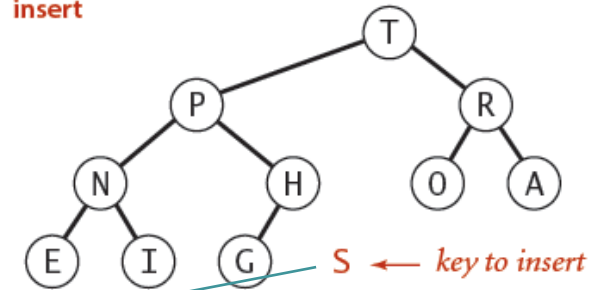
- Insert: Add node at end, then **swim** it up.
 - Cost: At most $1 + \log N$ compares.

```
void insert(heap h, int key)
{
    
}
```

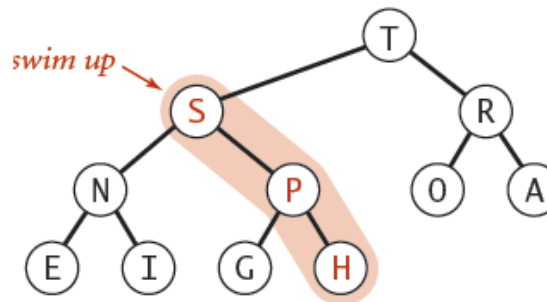
```
struct Heap {
    int *nodes;           // an array of nodes
    int capacity;         // array size of node or key, item
    int N;                // the number of nodes in the heap
    //
};
using heap = *Heap;
```

What is N now?

insert



swim up



heap coding

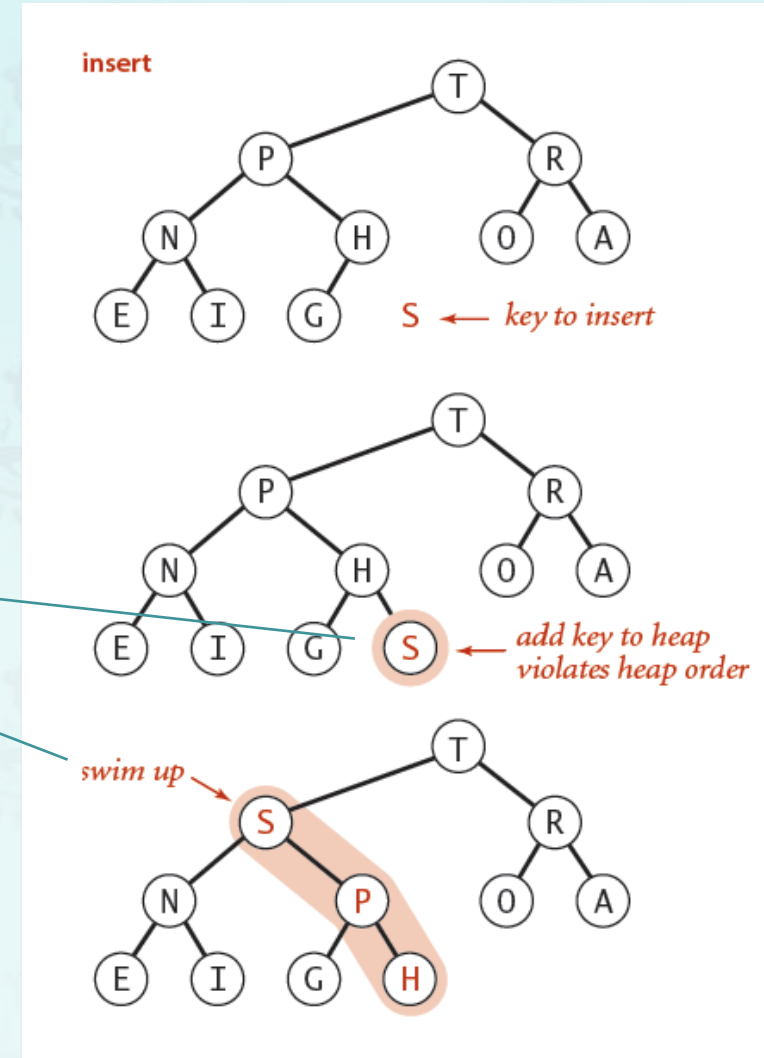
Insertion in a heap:

- Insert: Add node at end, then **swim** it up.
 - Cost: At most $1 + \log N$ compares.

```
void insert(heap h, int key)
{
    h->nodes[++h->N] = key;
    
}
```

```
struct Heap {
    int *nodes;           // an array of nodes
    int capacity;         // array size of node or key, item
    int N;                // the number of nodes in the heap
    //
};
using heap = *Heap;
```

```
void swim(heap h, int k)
void sink(heap h, int k)
```



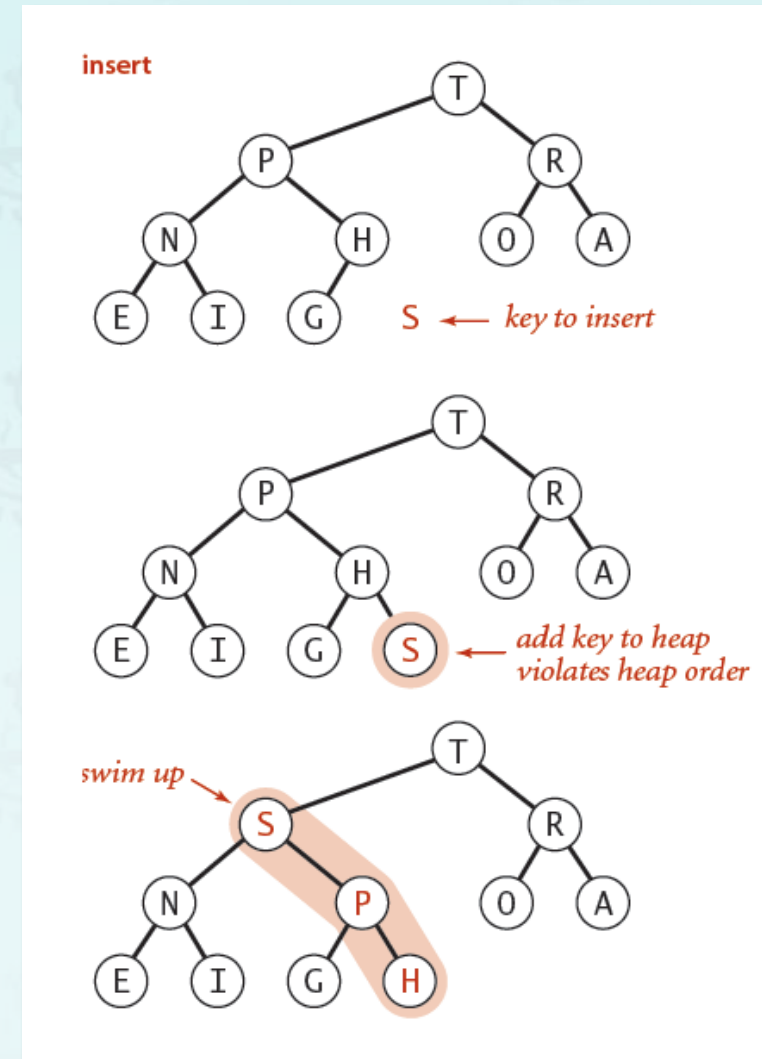
heap coding

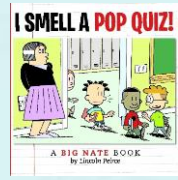
Insertion in a heap:

- Insert: Add node at end, then **swim** it up.
 - Cost: At most $1 + \log N$ compares.

```
void insert(heap h, int key)
{
    h->nodes[++h->N] = key;
    swim(h, h->N);
}
```

```
struct Heap {
    int *nodes;      // an array of nodes
    int capacity;    // array size of node or key, item
    int N;           // the number of nodes in the heap
    //
};
using heap = *Heap;
```



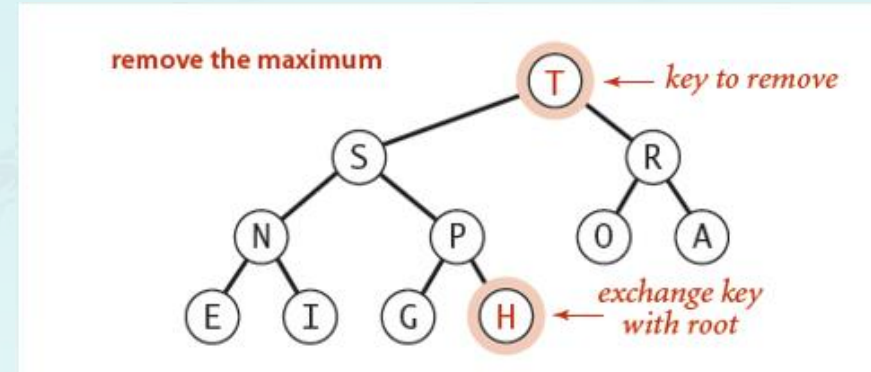


heap coding

(1) Delete the root (max or min) in a heap:

(2) How many times do comparisons occur for n nodes ? (select one):

n , $2n$, n^2 , $2 \log n$, $n \log n$, $\log n$



```
void delete(heap h) {  
  
  
}
```

← 2 or 3 lines of code

```
void swim(heap h, int k)  
void sink(heap h, int k)  
  
bool less(heap h, int p, int c)  
  
void swap(heap h, int p, int c)
```

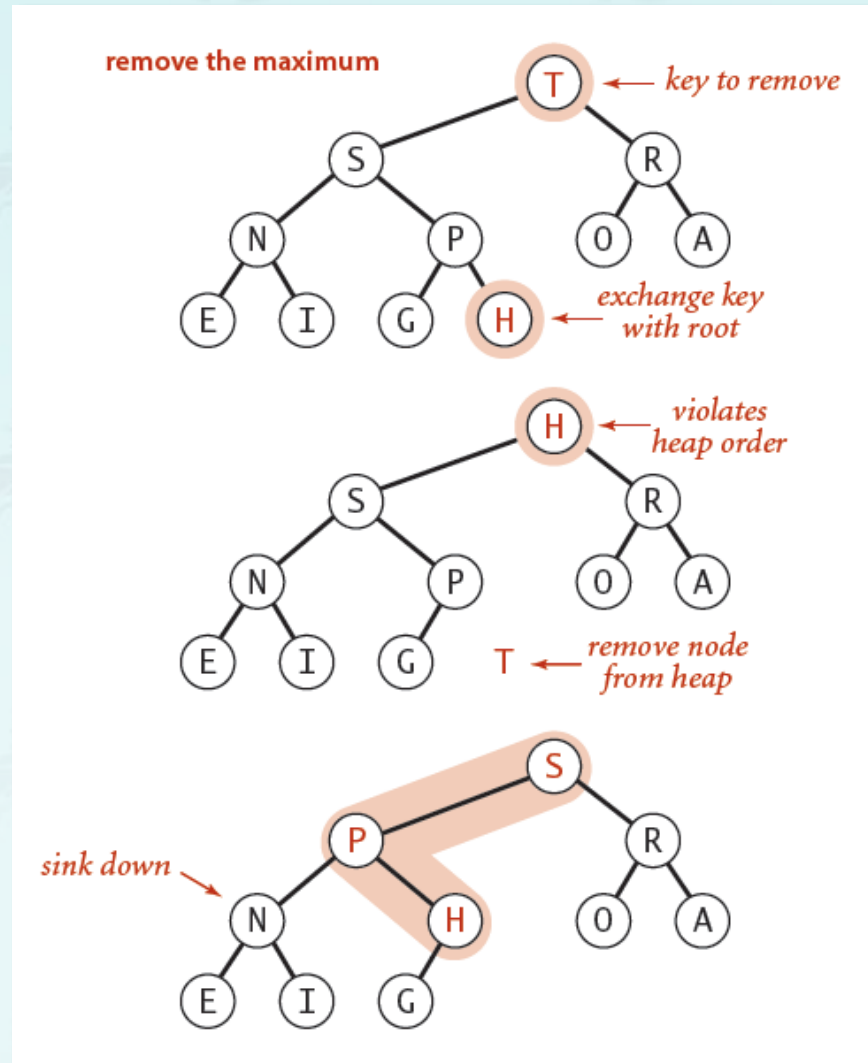

heap coding

Delete the root (max or min) in a heap:

- **Delete root:** Swap root with node at end, then sink it down.
- **Cost:** At most $2 \log N$ compares.

```
void delete(heap h) {  
  
}  
  
    swap(h, ..., ... );  
    sink(h, ...);  
}
```

```
void swim(heap h, int k)  
void sink(heap h, int k)  
  
bool less(heap h, int p, int c)  
  
void swap(heap h, int p, int c)
```



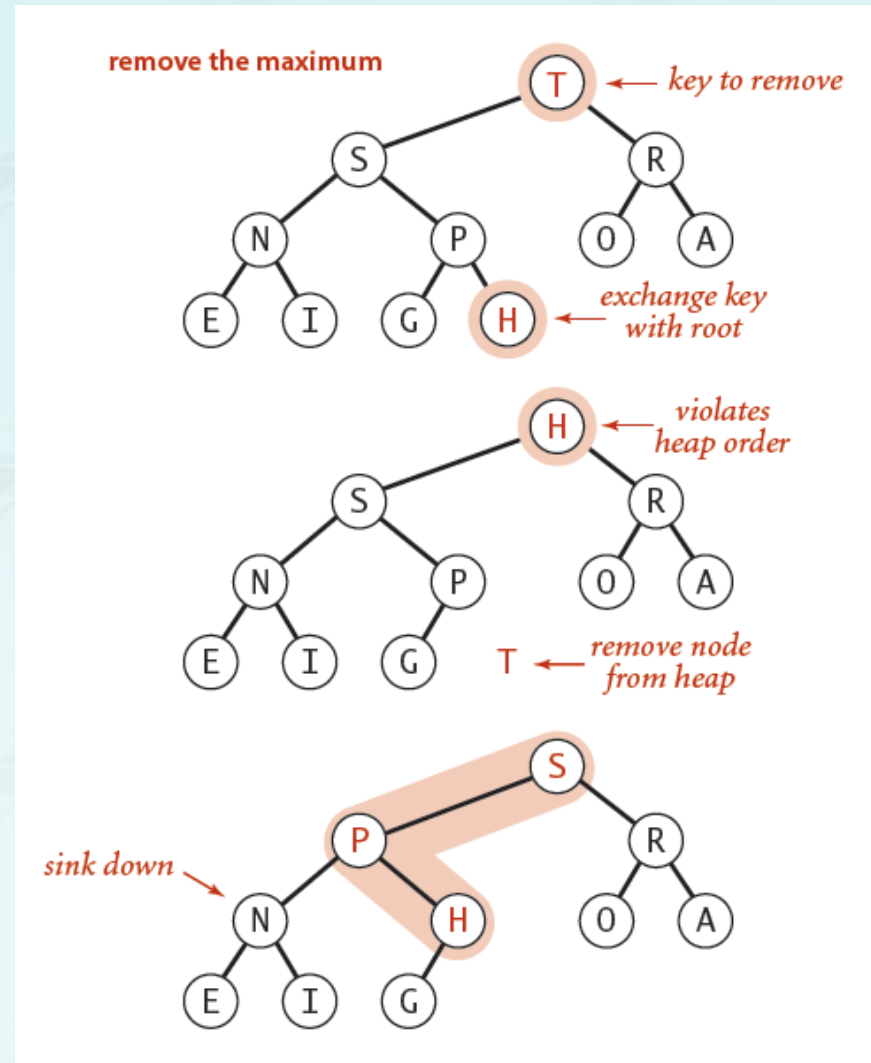
heap coding

Delete the root (max or min) in a heap:

- **Delete root:** Swap root with node at end, then sink it down.
- **Cost:** At most $2 \log N$ compares.

```
void delete(heap h) {  
      
}  
}
```

```
void swim(heap h, int k)  
void sink(heap h, int k)  
bool less(heap h, int p, int c)  
void swap(heap h, int p, int c)
```



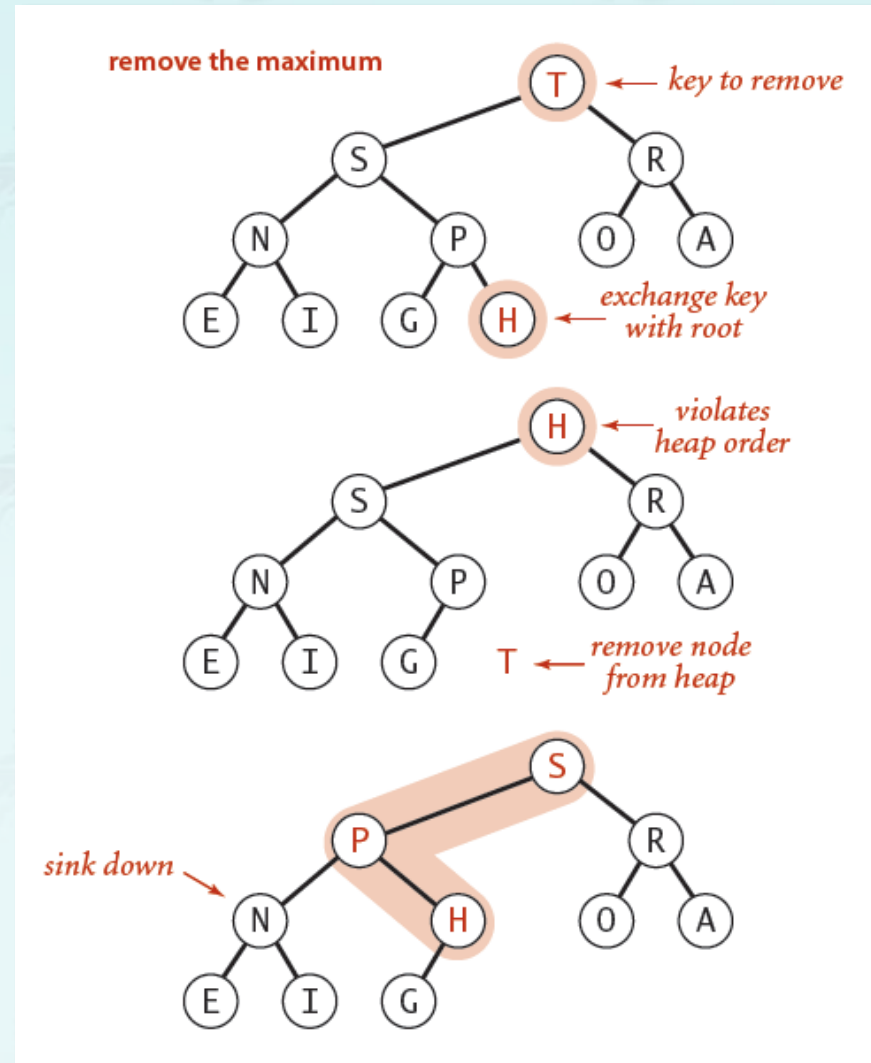
heap coding

Delete the root (max or min) in a heap:

- **Delete root:** Swap root with node at end, then sink it down.
- **Cost:** At most $2 \log N$ compares.

```
void delete(heap h) {  
    swap(h, 1, h->N--);  
      
}
```

```
void swim(heap h, int k)  
void sink(heap h, int k)  
  
bool less(heap h, int p, int c)  
void swap(heap h, int p, int c)
```



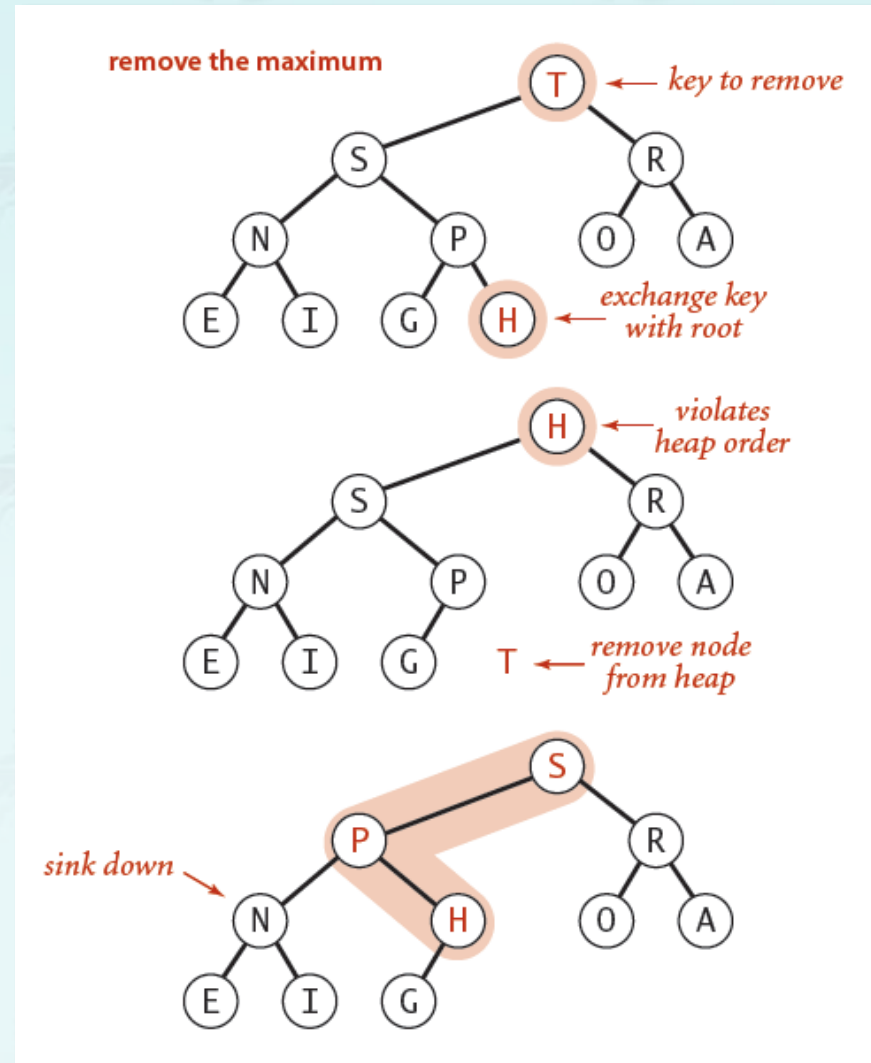
heap coding

Delete the root (max or min) in a heap:

- **Delete root:** Swap root with node at end, then sink it down.
- **Cost:** At most $2 \log N$ compares.

```
void delete(heap h) {  
    swap(h, 1, h->N--);  
    sink(h, 1);  
}
```

```
void swim(heap h, int k)  
void sink(heap h, int k)  
bool less(heap h, int p, int c)  
void swap(heap h, int p, int c)
```



Heap Coding

```
void clear(heap hp);           // deallocate heap
int size(heap hp);            // return nodes in heap currently
int level(int n);             // return level based on num of nodes
int capacity(heap hp);        // return its capacity (array size)
int reserve(heap hp, int capa); // reserve the array size (= capacity)
int full(heap hp);            // return true/false
int empty(heap hp);           // return true/false
void grow(heap hp, int key);   // add a new key
void trim(heap hp);           // delete a queue
int heapify(heap hp);          // convert a complete BT into a heap

// helper functions to support grow/trim functions
int less(heap hp, int i, int j); // used in max heap
int more(heap hp, int i, int j); // used in min heap
void swim(heap hp, int k);       // bubble up
void sink(heap hp, int k);       // tickle down
// helper functions to check heap invariant
int heapOrdered(heap hp);        // is heap[1..N] a heap?
```

Heap Coding

```
// return the number of items in heap
int size(heap hp) {
    return heap->N;
}
```

```
// Is this heap empty?
int empty(heap hp) {
    return (heap->N == 0) ? true : false;
}
```

```
// Is this heap full?
int full(heap hp) {
    return (heap->N == heap->capacity - 1) ? true : false;
}
```

Heap Coding

```
int less(heap hp, int i, int j) {  
    return heap->nodes[i] < heap->nodes[j];  
}
```

```
void swap(heap hp, int i, int j) {  
    int t = heap->nodes[i];  
    heap->nodes[i] = heap->nodes[j];  
    heap->nodes[j] = t;  
}
```

```
void swim(heap hp, int k) {  
  
}
```

```
void sink(heap hp, int k) {  
  
}
```

Heap Coding

```
void grow(heap hp, int key) {  
    cout << "YOUR CODE HERE\n";  
  
    // add key @ ++heap->N  
  
    // swim up @ heap->N  
  
}
```

```
void trim(heap hp) {  
    if (empty(heap)) return;  
  
    cout << "YOUR CODE HERE\n";  
  
}
```


Heap Coding

newCBT()	with a given array, instantiate a new complete binary tree its result is neither maxheap nor minheap.
heapify()	make a complete binary tree into a max/minheap
heapsort()	use max/min-heap to sort elements in heap
heapprint()	convert heap to tree for display purpose only

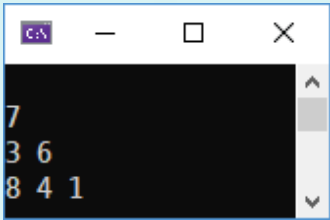
newCBT() – convert an int array to CBT

```
// instantiates a CBT with given data and its size.
heap newCBT(int *a, int n) {
    int capa = ?

    heap p = new Heap{ capa };

    p->N = n;
    for (int i = 0; i < n; i++)
        p->nodes[i + 1] = a[i];
    return p;
}
```

heapprint() – convert heap to tree using queue



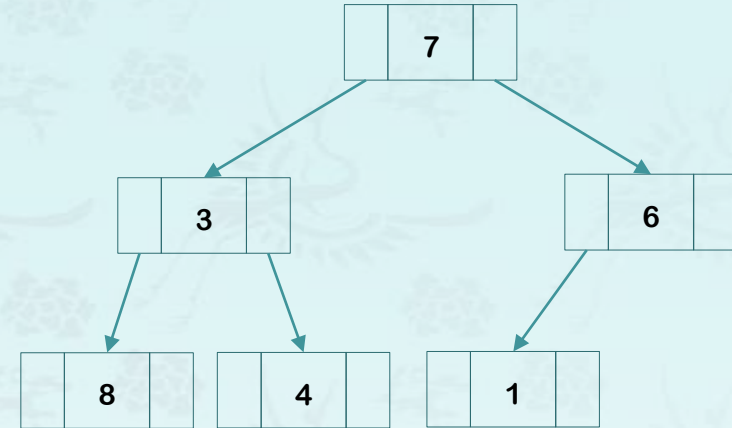
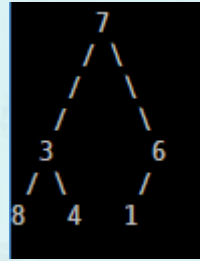
```
7
3 6
8 4 1
```



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

hp->nodes[]

hp->N



```
struct Heap {
    int *nodes;
    int capacity;
    int N;
    bool (*comp)(Heap*, int, int);
    Heap(int capa = 2) {
        capacity = capa;
        nodes = new int[capacity];
        N = 0;
        comp = nullptr;
    };
    ~Heap() {};
};
using heap = Heap*;
```

```
struct TreeNode {
    int key;
    TreeNode *left;
    TreeNode *right;
    TreeNode(const int k = 0,
              TreeNode* l = nullptr,
              TreeNode* r = nullptr) {
        key = k; left = l; right = r;
    }
    ~TreeNode() {}
};
using tree = TreeNode*;
```

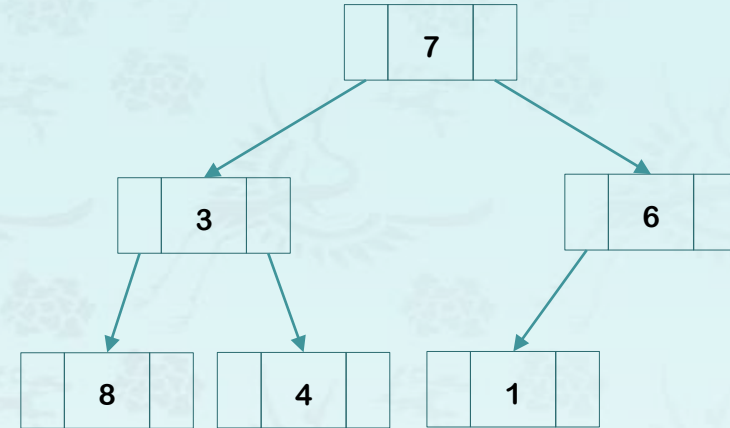
heapprint() – convert heap to tree using queue

```
C:\>
7
3 6
8 4 1
```

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

hp->nodes []

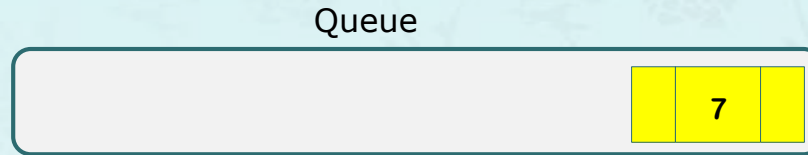
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
2. Enqueue the root node.
3. Loop through from **the CBT nodes[2] to nodes[N]**
 - A. Make a **new node from nodes[i]**.
 - B. Get a **tree node** in the queue.
 - C. If the left of the tree node doesn't exist,
set the new node to the left of the tree node.
else if the right of this tree node doesn't exist,
set the new node to the right of the tree node.
 - D. If this tree node is full, pop (or dequeue) it.
 - E. enqueue the new node (to add children later if any).
4. treeprint(root)

heapprint() – convert heap to tree using queue

```
C:\N - □ ×
7
3 6
8 4 1
```



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

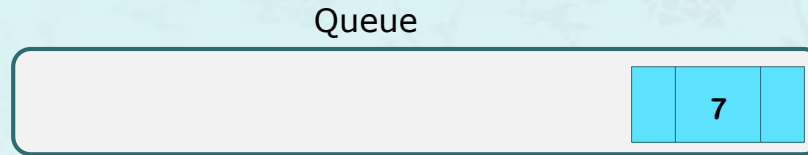
hp->nodes []

hp->N

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heapprint() – convert heap to tree using queue

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C:\>
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3 6
8 4 1
```



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

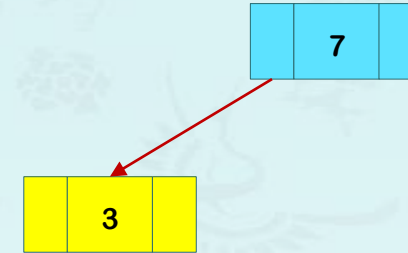
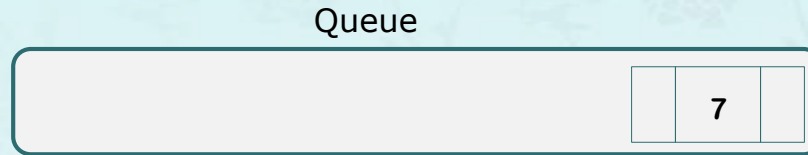
hp->nodes []

hp->N

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heapprint() – convert heap to tree using queue

```
C:\N - [X]
7
3 6
8 4 1
```



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

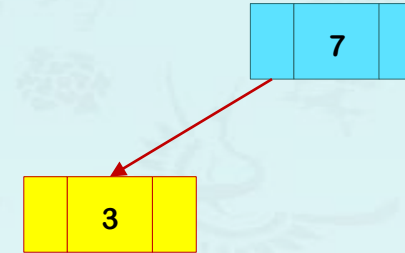
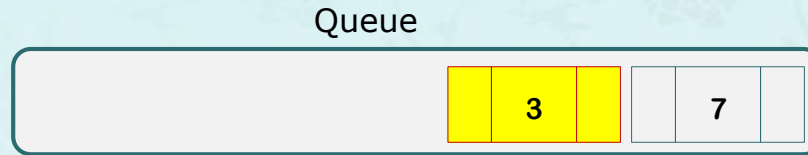
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hp->N

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heapprint() – convert heap to tree using queue

```
C:\N - □ ×
7
3 6
8 4 1
```



0	1	2	3	4	5	6	7
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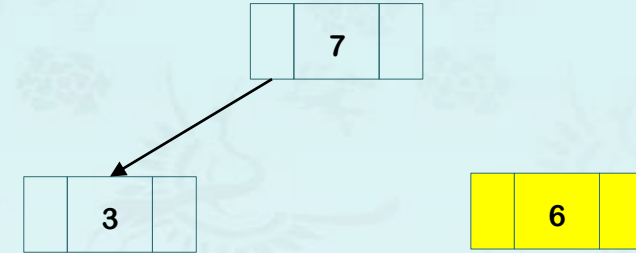
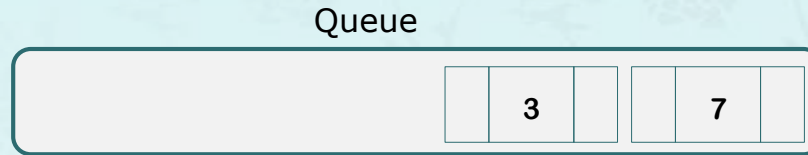
hp->nodes []

hp->N

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4. treeprint(root)

heapprint() – convert heap to tree using queue

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8 4 1
```



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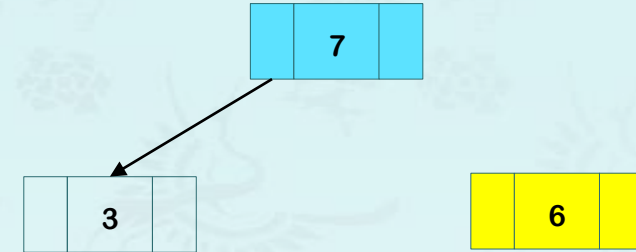
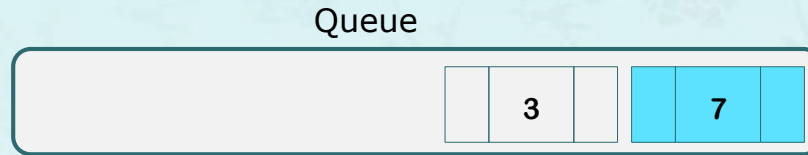
hp->nodes []

hp->N

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4. treeprint(root)

heapprint() – convert heap to tree using queue

```
C:\N - □ ×
7
3 6
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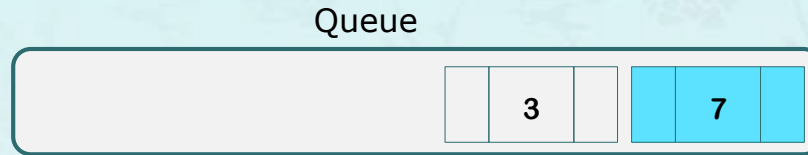
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hp->N

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heapprint() – convert heap to tree using queue

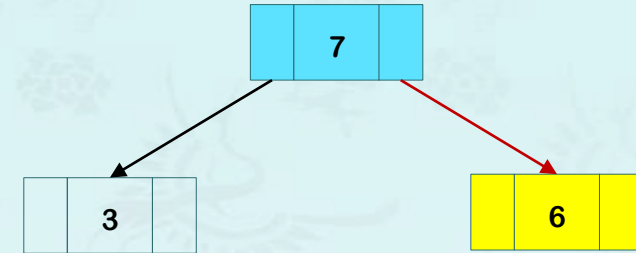
```
C:\N - □ ×
7
3 6
8 4 1
```



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

hp->nodes []

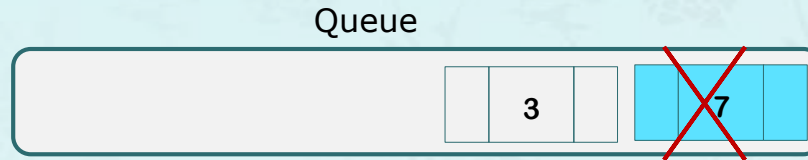
hp->N



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heapprint() – convert heap to tree using queue

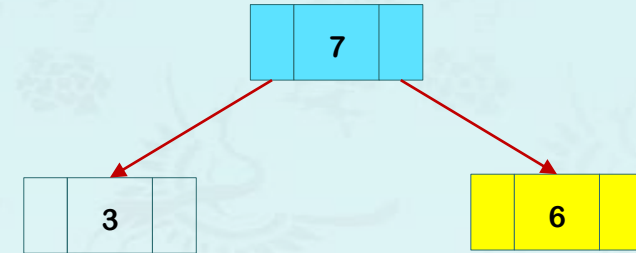
```
C:\N - [X]
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0	1	2	3	4	5	6	7
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hp->nodes []

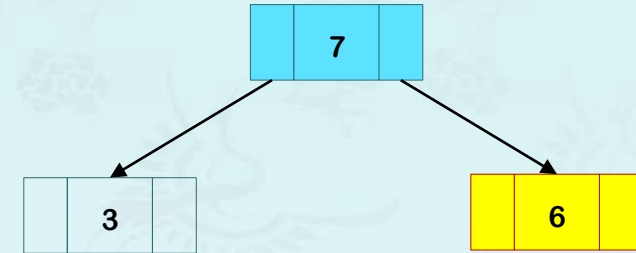
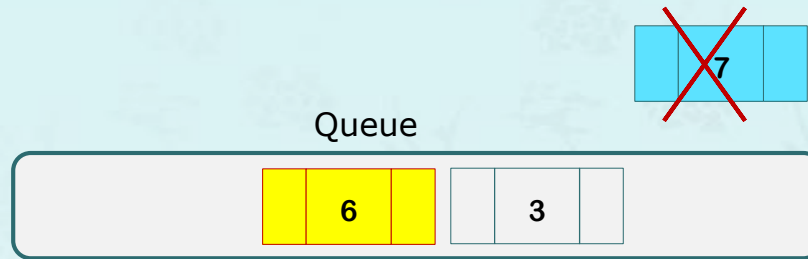
hp->N



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4. treeprint(root)

heapprint() – convert heap to tree using queue

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C:\N - [X]
7
3 6
8 4 1
```



0	1	2	3	4	5	6	7
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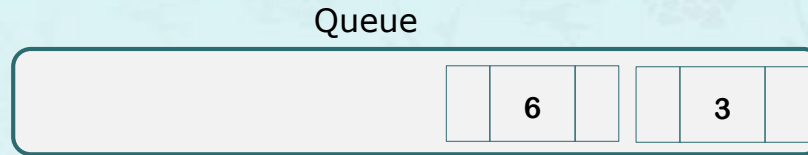
hp->nodes []

hp->N

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4. treeprint(root)

heapprint() – convert heap to tree using queue

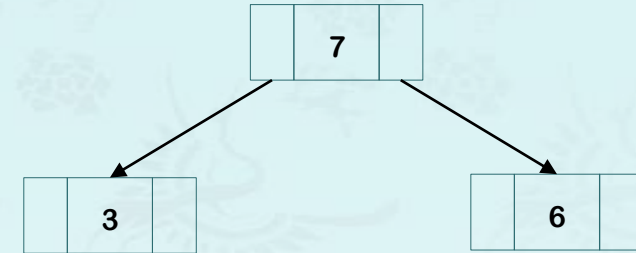
```
C:\N - [X]
7
3 6
8 4 1
```



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

hp->nodes []

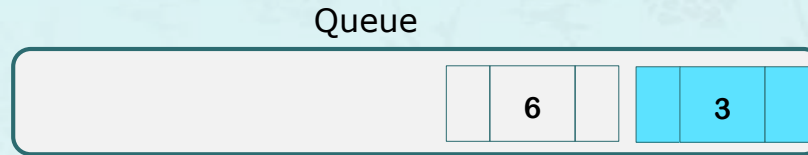
hp->N



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heapprint() – convert heap to tree using queue

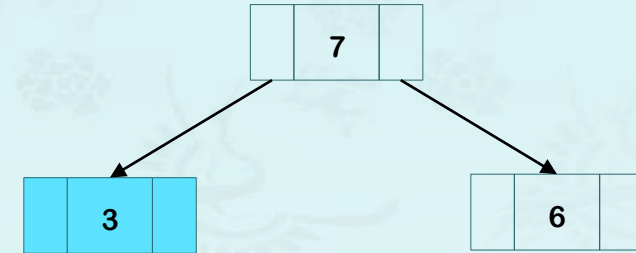
```
C:\N - □ ×
7
3 6
8 4 1
```



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

hp->nodes []

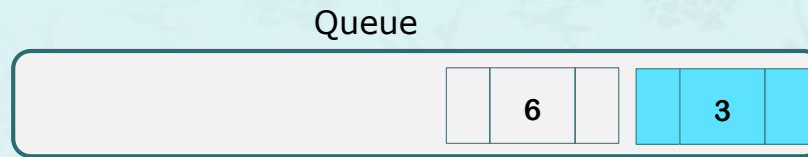
hp->N



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set the new node to the right of the tree node.
 - D. If this tree node is full, pop (or dequeue) it.
 - E. enqueue the new node (to add children later if any).
4. treeprint(root)

heapprint() – convert heap to tree using queue

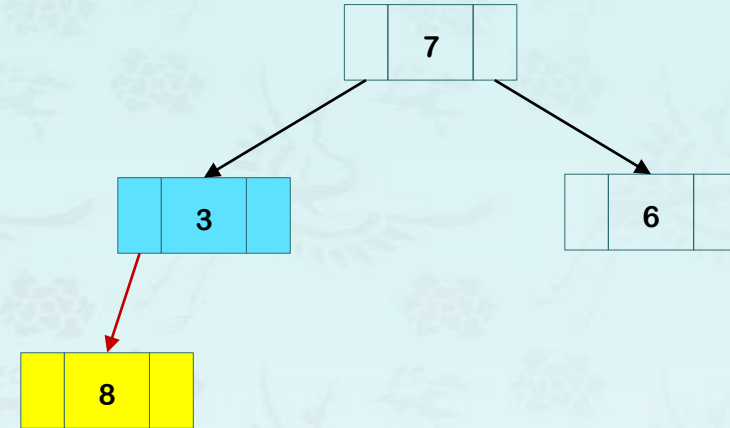
```
C:\>
7
3 6
8 4 1
```



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

hp->nodes []

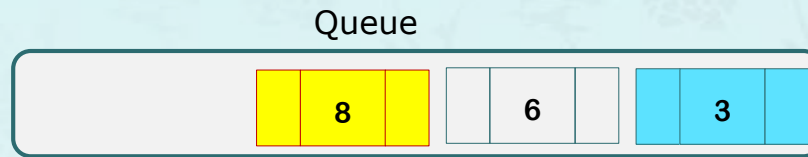
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
2. Enqueue the root node.
3. Loop through from **the CBT nodes[2] to nodes[N]**
 - A. **Make a new node from nodes[i].**
 - B. **Get a tree node in the queue.**
 - C. **If the left of the tree node doesn't exist, set the new node to the left of the tree node.**
else if the right of this tree node doesn't exist,
set the new node to the right of the tree node.
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4. treeprint(root)

heapprint() – convert heap to tree using queue

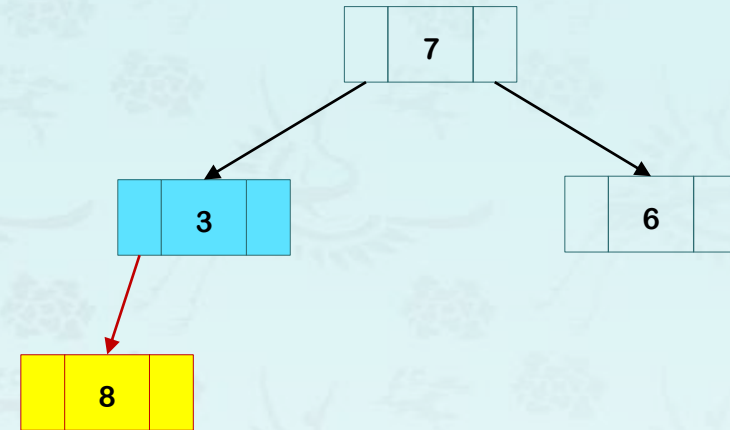
```
C:\>
7
3 6
8 4 1
```



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

hp->nodes []

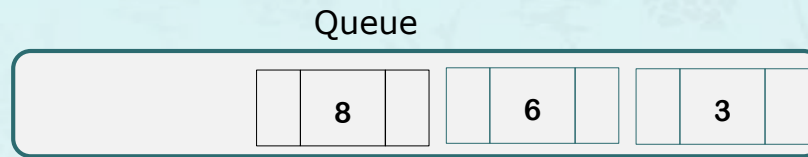
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
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 - D. If this tree node is full, pop (or dequeue) it.
 - E. **enqueue the new node (to add children later if any).**
4. treeprint(root)

heapprint() – convert heap to tree using queue

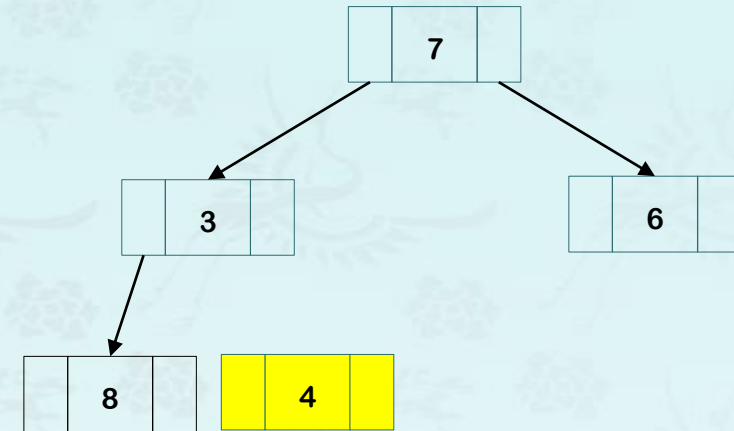
```
C:\N - [X]
7
3 6
8 4 1
```



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

hp->nodes []

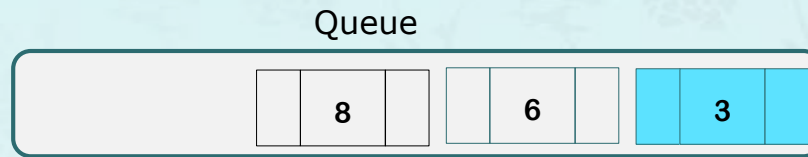
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
2. Enqueue the root node.
3. Loop through from **the CBT nodes[2] to nodes[N]**
 - A. **Make a new node from nodes[i].**
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4. treeprint(root)

heapprint() – convert heap to tree using queue

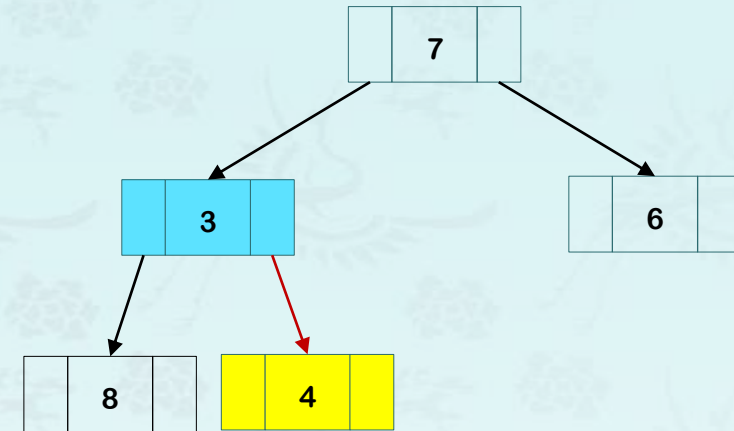
```
C:\>
7
3 6
8 4 1
```



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

hp->nodes []

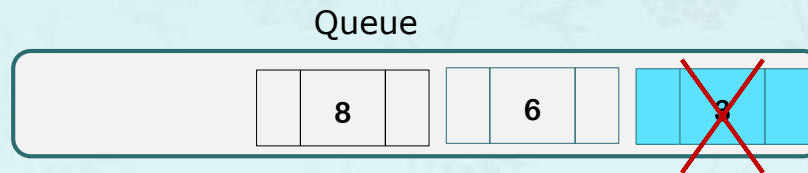
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
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4. treeprint(root)

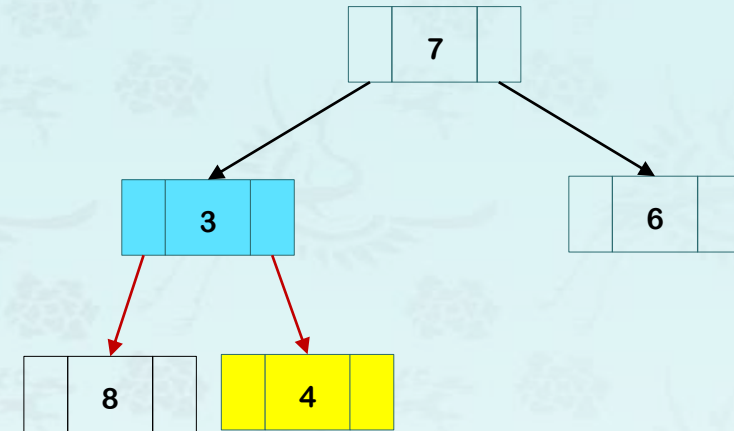
heapprint() – convert heap to tree using queue

```
C:\>
7
3 6
8 4 1
```



hp->nodes []

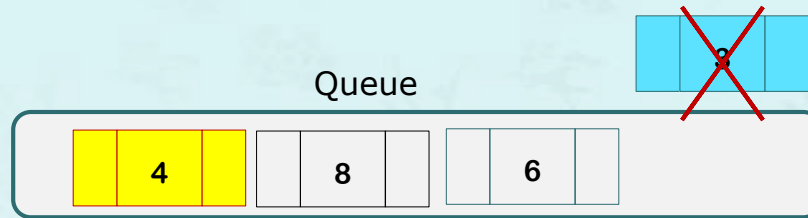
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
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4. treeprint(root)

heapprint() – convert heap to tree using queue

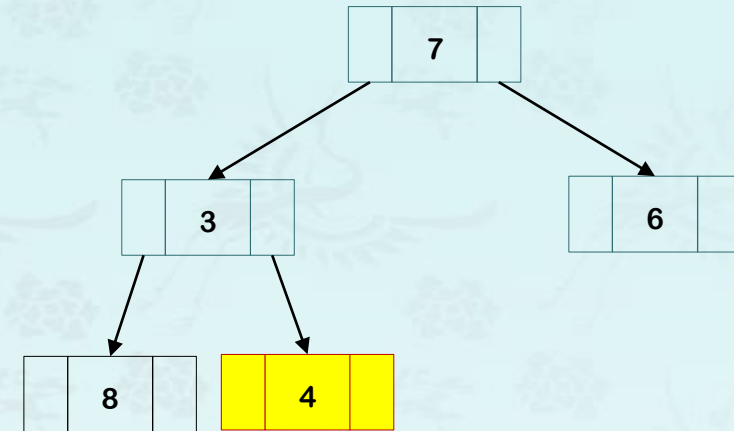
```
C:\>
7
3 6
8 4 1
```



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

hp->nodes []

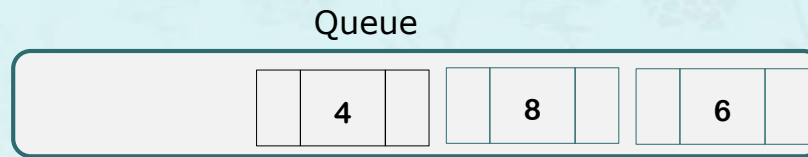
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
2. Enqueue the root node.
3. Loop through from **the CBT nodes[2] to nodes[N]**
 - A. **Make a new node from nodes[i].**
 - B. **Get a tree node in the queue.**
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set the new node to the left of the tree node.
else if the right of this tree node doesn't exist,
set the new node to the right of the tree node.
 - D. If this tree node is full, pop (or dequeue) it.
 - E. **enqueue the new node (to add children later if any).**
4. treeprint(root)

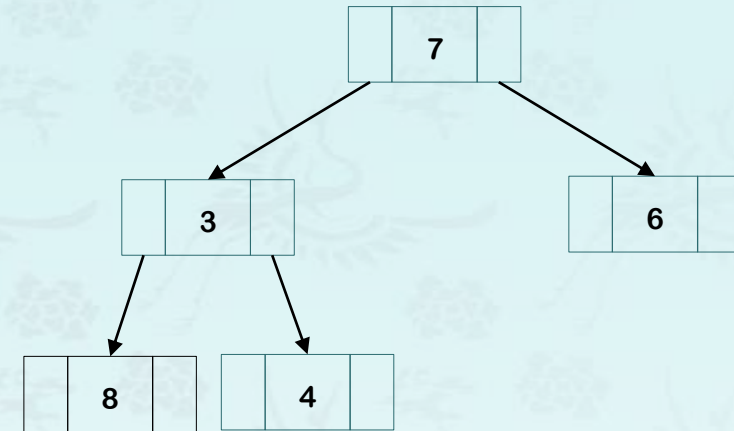
heapprint() – convert heap to tree using queue

```
C:\N - [X]
7
3 6
8 4 1
```



hp->nodes []

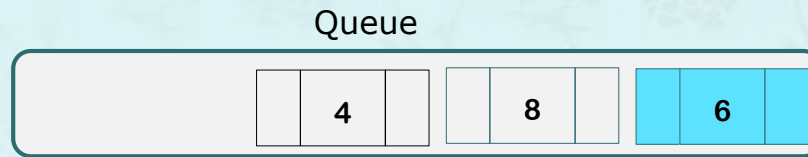
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
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 - A. Make a **new node from nodes[i]**.
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set the new node to the left of the tree node.
else if the right of this tree node doesn't exist,
set the new node to the right of the tree node.
 - D. If this tree node is full, pop (or dequeue) it.
 - E. enqueue the new node (to add children later if any).
4. treeprint(root)

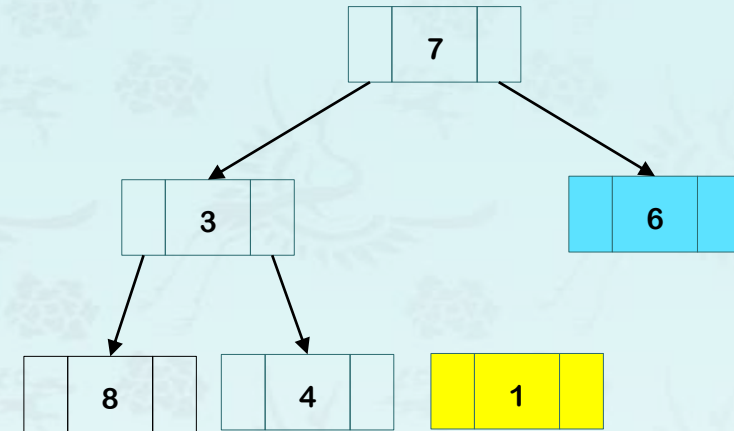
heapprint() – convert heap to tree using queue

```
C:\>
7
3 6
8 4 1
```



hp->nodes []

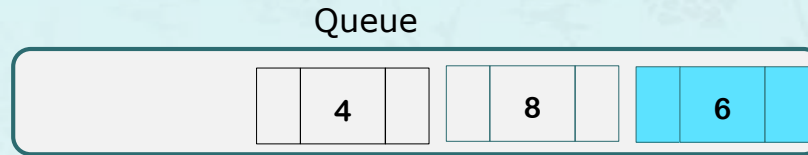
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
2. Enqueue the root node.
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4. treeprint(root)

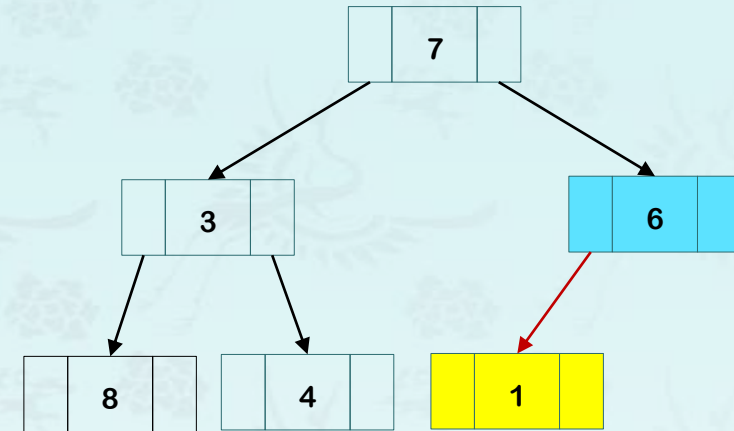
heapprint() – convert heap to tree using queue

```
C:\N - □ ×
7
3 6
8 4 1
```



hp->nodes []

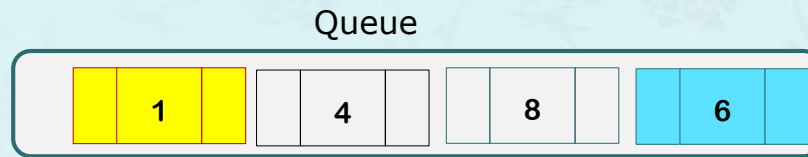
hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
2. Enqueue the root node.
3. Loop through from **the CBT nodes[2] to nodes[N]**
 - A. **Make a new node from nodes[i].**
 - B. **Get a tree node in the queue.**
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 - D. If this tree node is full, pop (or dequeue) it.
 - E. enqueue the new node (to add children later if any).
4. treeprint(root)

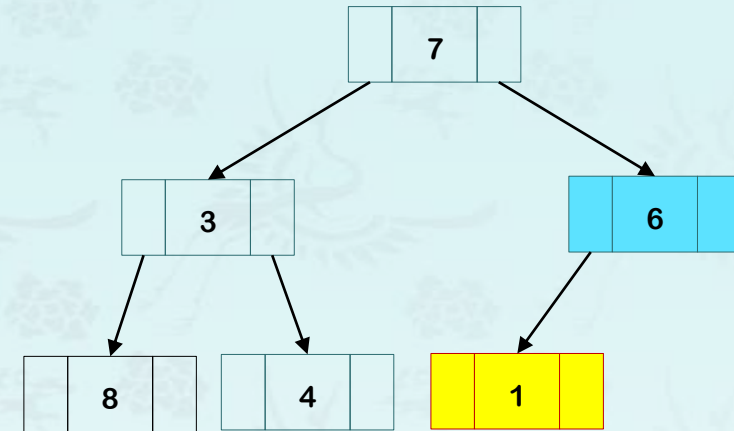
heapprint() – convert heap to tree using queue

```
C:\>
7
3 6
8 4 1
```



hp->nodes []

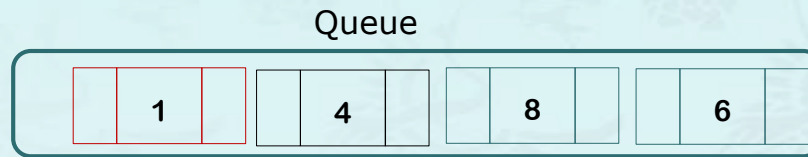
hp->N



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2. Enqueue the root node.
3. Loop through from **the CBT nodes[2] to nodes[N]**
 - A. **Make a new node from nodes[.]**.
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 - D. If this tree node is full, pop (or dequeue) it.
 - E. **enqueue the new node (to add children later if any).**
4. treeprint(root)

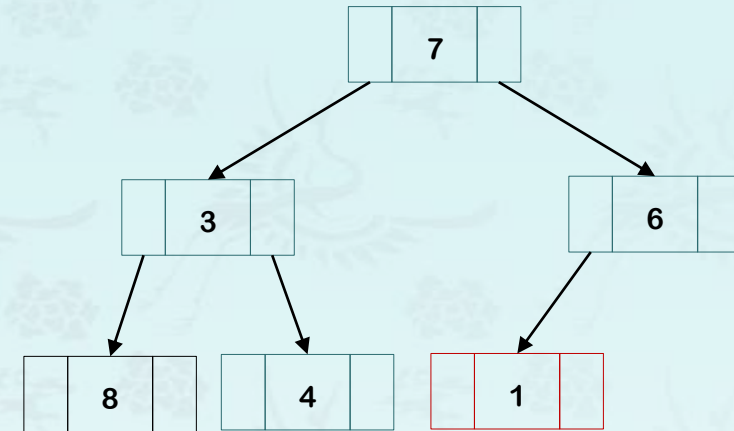
heapprint() – convert heap to tree using queue

```
C:\N - □ ×
7
3 6
8 4 1
```



hp->nodes []

hp->N



1. Create the **tree (root) node** with the first key from CBT (or **nodes[1]**).
2. Enqueue the root node.
3. **Loop through from the CBT nodes[2] to nodes[N]**
 - A. Make a **new node from nodes[]**.
 - B. Get a **tree node** in the queue.
 - C. If the left of the tree node doesn't exist,
set the new node to the left of the tree node.
else if the right of this tree node doesn't exist,
set the new node to the right of the tree node.
 - D. If this tree node is full, pop (or dequeue) it.
 - E. enqueue the new node (to add children later if any).
4. treeprint(root)

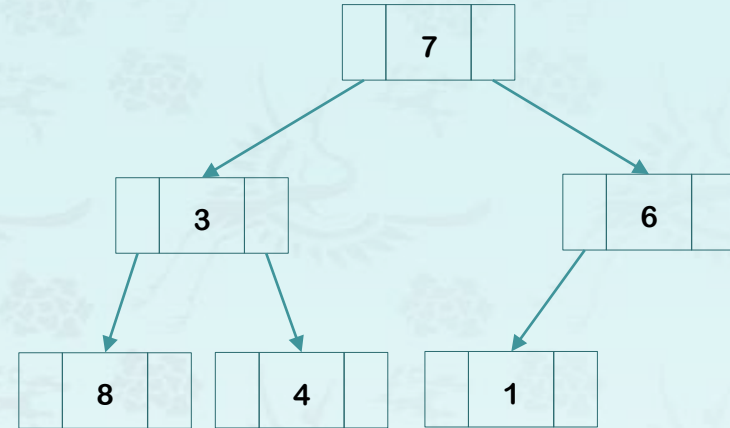
heapprint() – convert heap to tree using recursion



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

hp->nodes []

hp->N



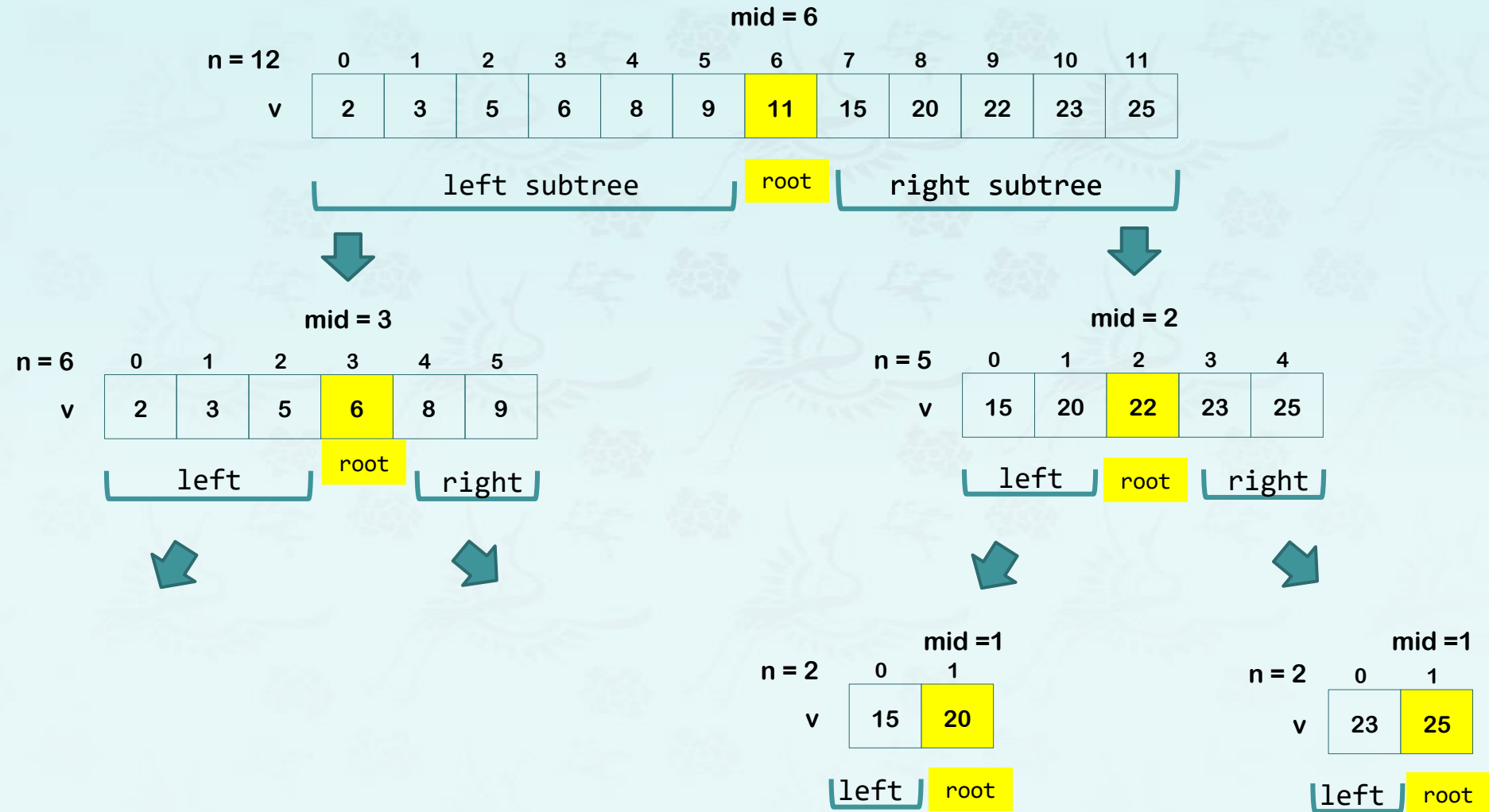
Building AVL tree from BST in $O(n)$ – Review

mid = 6

n = 12	0	1	2	3	4	5	6	7	8	9	10	11
v	2	3	5	6	8	9	11	15	20	22	23	25

left subtree root right subtree

Building AVL tree from BST in $O(n)$ – Review



Building AVL tree from BST in $O(n)$ – Review

```
// rebuilds an AVL tree with a list of keys sorted.  
// v - an array of keys sorted, n - the array size
```

```
tree buildAVL(int* v, int n) {  
    if (n <= 0) return nullptr;
```

```
    int mid = n / 2;
```

```
    return root;
```

```
}
```

```
tree rebalanceTree(tree root) {  
    if (root == nullptr) return nullptr;  
    vector<int> v;          // get keys sorted  
    inorder(root, v);      //  $O(n)$   
    clear(root);
```

```
    tree new_root = buildAVL(v.data(), v.size()); //  $O(n)$   
    return new_root;
```

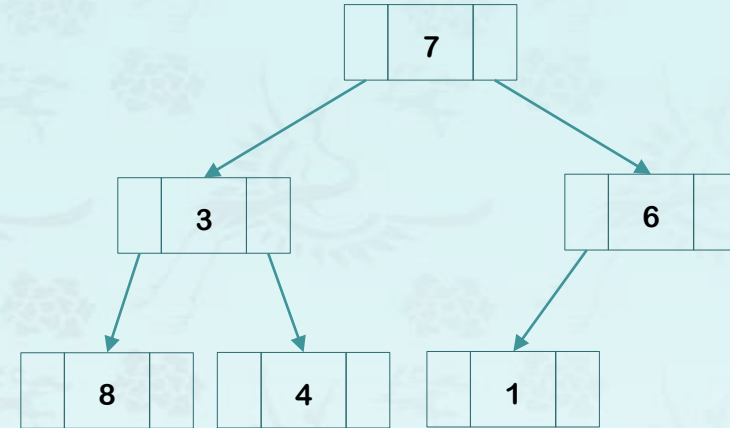
```
}
```

heapprint() – convert heap to tree using recursion

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

hp->nodes []

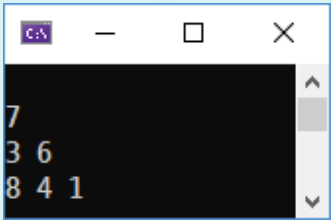
hp->N



Create a recursive function that creates a binary tree from an int array. This function takes an int array, starting index, and size of the array and returns the root as shown below:

```
tree _buildBT(int *nodes, int i, int n) {  
    1. If  $i > n$ , return nullptr – terminate condition  
    2. Create the tree (root) node with nodes[i].  
        A. Invoke _buildBT() for all its left children (or  $i * 2$ ).  
           Set its return to the left child of the root.  
        B. Invoke _buildBT() for all its right children (or  $i * 2 + 1$ ).  
           Set its return to the right child of the root.  
    3. return root  
}
```

heapprint() – convert heap to tree using recursion



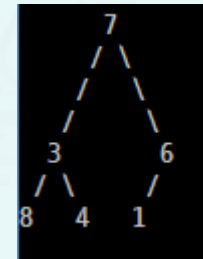
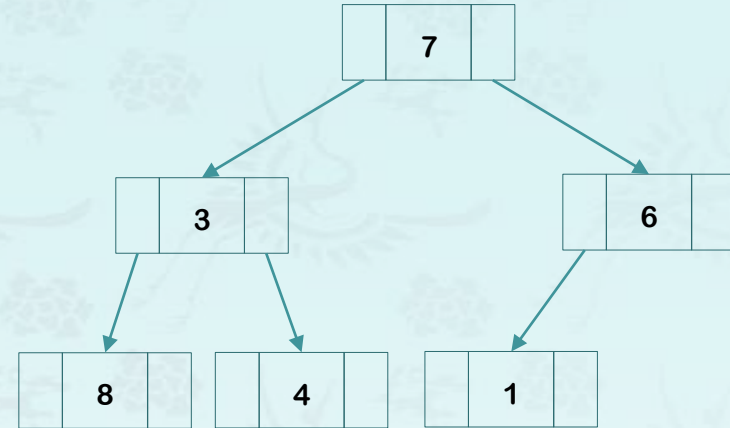
```
C:\>  
7  
3 6  
8 4 1
```

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

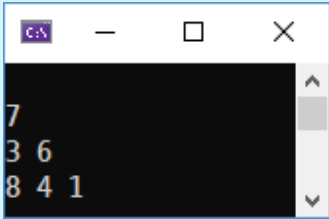
hp->nodes[]

hp->N

```
tree _buildBT(int *nodes, int i, int n) {  
    _____  
    _____  
    _____  
    _____  
    return root;  
}
```



heapprint() – convert heap to tree using recursion



```
C:\>  
7  
3 6  
8 4 1
```

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



hp->nodes []

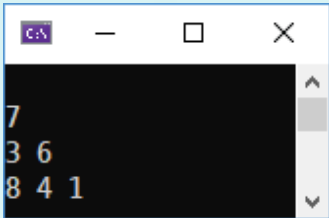
hp->N

```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

```
void heapprint(heap p) {  
    if (empty(p)) return;  
    tree root = _buildBT(p->nodes, 1, size(p));  
    treeprint(root);  
}
```

```
tree _buildBT(*nodes, i=1, n=6) { }
```

heapprint() – convert heap to tree using recursion



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



hp->nodes[]

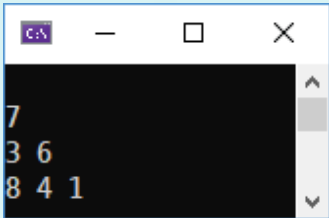
hp->N

```
tree _buildBT(int *nodes, int i, int n) {
    if (i > n) return nullptr;

    tree root = new TreeNode{ nodes[i] };
    root->left  = _buildBT(nodes, i * 2, n);
    root->right = _buildBT(nodes, i * 2 + 1, n);
    return root;
}
```

```
tree _buildBT(*nodes, i=1, n=6) { }
```

heapprint() – convert heap to tree using recursion



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

hp->nodes[]

hp->N



```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

ret. addr. root=6

```
tree _buildBT(*nodes, i=1, n=6) { }
```

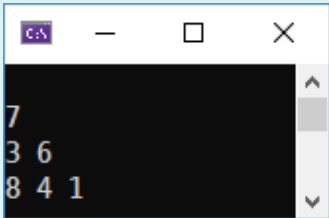
```
tree _buildBT(*nodes, i=2, n=6) { }
```

System
Stack

i=1, n=6
ret. addr.



heapprint() – convert heap to tree using recursion



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

hp->nodes[]

hp->N



```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

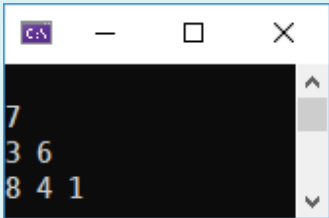
```
tree _buildBT(*nodes, i=2, n=6) { }
```

System
Stack

i=1, n=6
ret. addr.



heapprint() – convert heap to tree using recursion



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

hp->nodes[]

hp->N

```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

```
tree _buildBT(*nodes, i=2, n=6) { }
```

	7	
--	---	--

	3	
--	---	--

System
Stack

i=1, n=6
ret. addr.

	6	
--	---	--

heapprint() – convert heap to tree using recursion

```

7
3 6
8 4 1
    
```

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

hp->nodes[]

hp->N

```

tree _buildBT(int *nodes, int i, int n) {
    if (i > n) return nullptr;

    tree root = new TreeNode{ nodes[i] };
    root->left  = _buildBT(nodes, i * 2, n);
    root->right = _buildBT(nodes, i * 2 + 1, n);
    return root;
}
    
```

ret. addr. root(3)



	7	
--	---	--

	3	
--	---	--

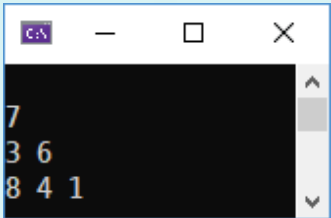
tree _buildBT(*nodes, i=2, n=6, { }

tree _buildBT(*nodes, i=4, n=6) { }

System Stack

i=2, n=6 ret. addr.	3
i=1, n=6 ret. addr.	6

heapprint() – convert heap to tree using recursion



```
7
3 6
8 4 1
```

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

hp->nodes[]

hp->N



```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

```
tree _buildBT(*nodes, i=4, n=6) { }
```

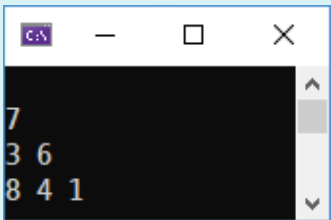
	7	
--	---	--

	3	
--	---	--

System
Stack

i=2, n=6 ret. addr.	3	
i=1, n=6 ret. addr.	6	

heapprint() – convert heap to tree using recursion



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

hp->nodes []

hp->N



	8	
--	---	--

	3	
--	---	--

	7	
--	---	--

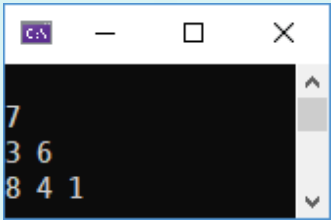
```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

```
tree _buildBT(*nodes, i=4, n=6) { }
```

System Stack

i=2, n=6 ret. addr.	3
i=1, n=6 ret. addr.	6

heapprint() – convert heap to tree using recursion



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

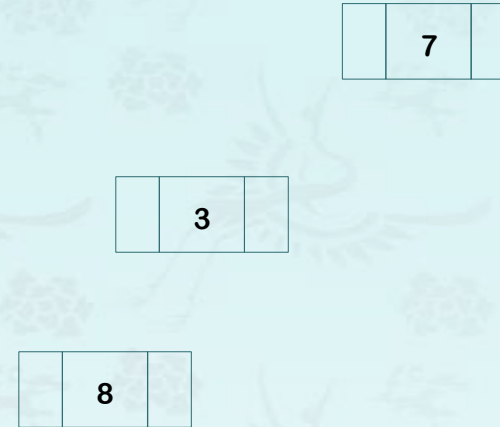
hp->nodes[]

hp->N

```
tree _buildBT(int *nodes, int i, int n) {
    if (i > n) return nullptr;

    tree root = new TreeNode{ nodes[i] };
    root->left  = _buildBT(nodes, i * 2, n);
    root->right = _buildBT(nodes, i * 2 + 1, n);
    return root;
}
```

ret. addr. root(8)



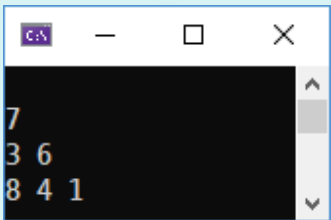
tree _buildBT(*nodes, i=4, n=6) { }

tree _buildBT(*nodes, i=8, n=6) { }

System
Stack

i=4, n=6 ret. addr.	8
i=2, n=6 ret. addr.	3
i=1, n=6 ret. addr.	6

heapprint() – convert heap to tree using recursion



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

hp->nodes []

hp->N



	8	
--	---	--

	3	
--	---	--

	7	
--	---	--

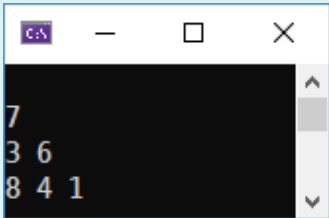
```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

```
tree _buildBT(*nodes, i=8, n=6) { }
```

System
Stack

i=4, n=6 ret. addr.	8
i=2, n=6 ret. addr.	3
i=1, n=6 ret. addr.	6

heapprint() – convert heap to tree using recursion



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

hp->nodes[]

hp->N

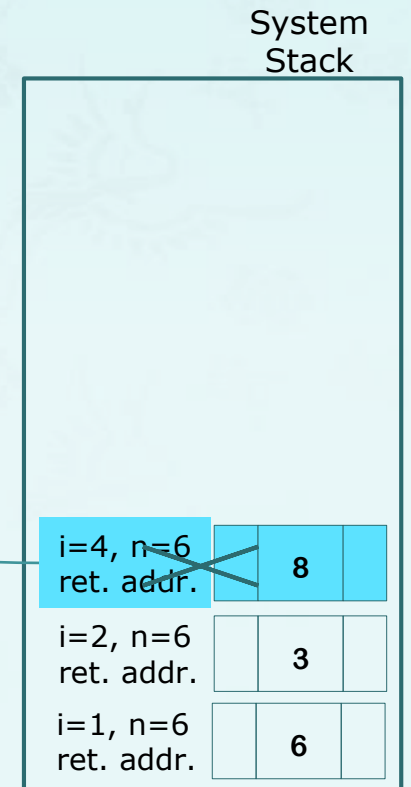
```
tree _buildBT(int *nodes, int i, int n) {
    if (i > n) return nullptr;

    tree root = new TreeNode{ nodes[i] };
    root->left = _buildBT(nodes, i * 2, n);
    root->right = _buildBT(nodes, i * 2 + 1, n);
    return root;
}
```

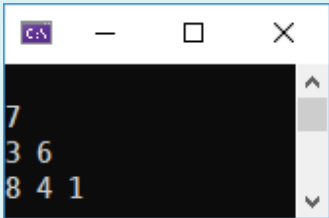


i=4, n=6, root(8), root->left = nullptr

pop stack



heapprint() – convert heap to tree using recursion



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

hp->nodes[]

hp->N

```
tree _buildBT(int *nodes, int i, int n) {
    if (i > n) return nullptr;

    tree root = new TreeNode{ nodes[i] };
    root->left  = _buildBT(nodes, i * 2, n);
    root->right = _buildBT(nodes, i * 2 + 1, n);
    return root;
}
```

ret. addr. root(8)



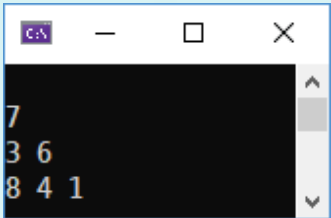
i=4, n=6, root(8), root->left = nullptr

tree _buildBT(*nodes,i=4*2+1,n=6){}

System
Stack

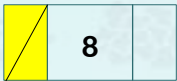
i=4, n=6 ret. addr.	8
i=2, n=6 ret. addr.	3
i=1, n=6 ret. addr.	6

heapprint() – convert heap to tree using recursion



hp->nodes []

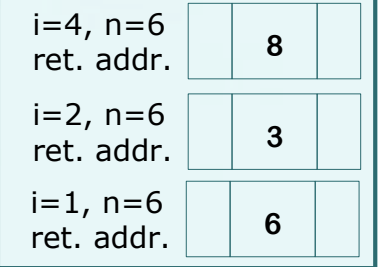
hp->N



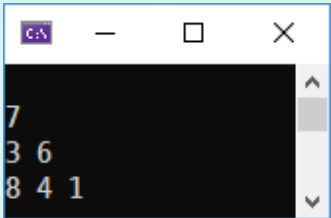
```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

```
tree _buildBT(*nodes, i=9, n=6) { }
```

System Stack



heapprint() – convert heap to tree using recursion

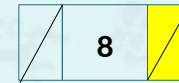


0	1	2	3	4	5	6	7
	7	3	6	8	4	1	

hp->nodes[]

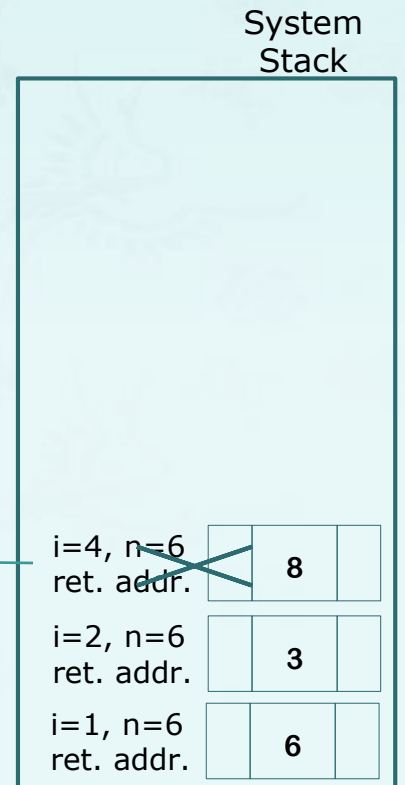
hp->N

```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```

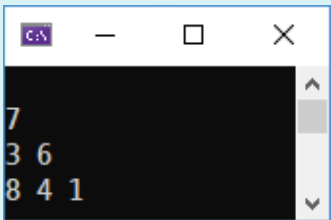


i=4, n=6, root(8), root->right = nullptr

pop stack



heapprint() – convert heap to tree using recursion

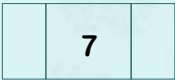
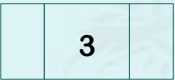
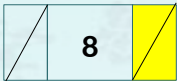


0	1	2	3	4	5	6	7
	7	3	6	8	4	1	

hp->nodes []

hp->N

```
tree _buildBT(int *nodes, int i, int n) {  
    if (i > n) return nullptr;  
  
    tree root = new TreeNode{ nodes[i] };  
    root->left  = _buildBT(nodes, i * 2, n);  
    root->right = _buildBT(nodes, i * 2 + 1, n);  
    return root;  
}
```



```
i=4, n=6, root(8), root->right = nullptr  
return root(8)
```

System Stack

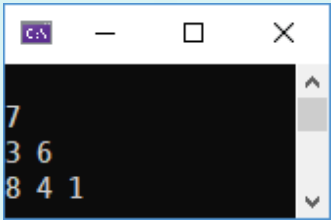
i=2, n=6
ret. addr.

3

i=1, n=6
ret. addr.

6

heapprint() – convert heap to tree using recursion



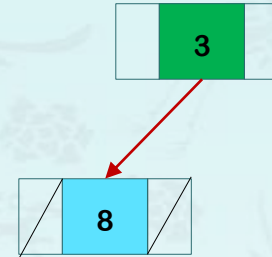
0	1	2	3	4	5	6	7
	7	3	6	8	4	1	

hp->nodes[]

hp->N

```
tree _buildBT(int *nodes, int i, int n) {
    if (i > n) return nullptr;

    tree root = new TreeNode{ nodes[i] };
    root->left = _buildBT(nodes, i * 2, n);
    root->right = _buildBT(nodes, i * 2 + 1, n);
    return root;
}
```



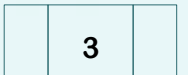
i=9, n=6, root(8), root->right = nullptr

return root(8)

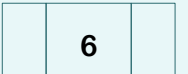
i=2, n=6, root(3) root->left = root(8)

System
Stack

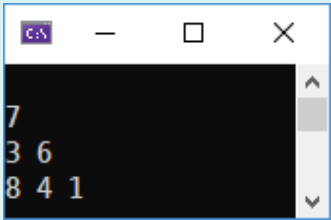
i=2, n=6
ret. addr.



i=1, n=6
ret. addr.



heapprint() – convert heap to tree using recursion



```
7
3 6
8 4 1
```

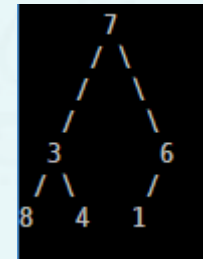
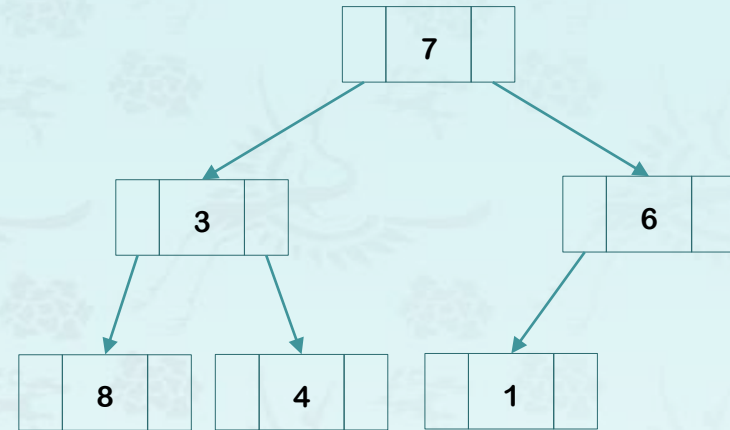
0	1	2	3	4	5	6	7
	7	3	6	8	4	1	

hp->nodes[]

hp->N

```
tree _buildBT(int *nodes, int i, int n) {
    if (i > n) return nullptr;

    tree root = new TreeNode{ nodes[i] };
    root->left  = _buildBT(nodes, i * 2, n);
    root->right = _buildBT(nodes, i * 2 + 1, n);
    return root;
}
```



heap

- complete binary tree (review)
- heap and priority queues (Chapter 9)
- binary heap and min-heap
- max-heap demo
- *max-heap coding*
- heapsort (Chapter 7)