

Priority Queues: Binary Heaps

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Data Structures
Data Structures and Algorithms

Outline

- 1 Binary Trees
- 2 Basic Operations
- 3 Complete Binary Trees
- 4 Pseudocode
- 5 Heap Sort
- 6 Final Remarks

Definition

Binary max-heap is a binary tree (each node has zero, one, or two children) where the value of each node is at least the values of its children.

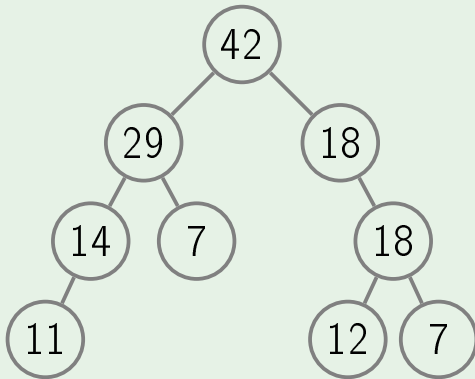
Definition

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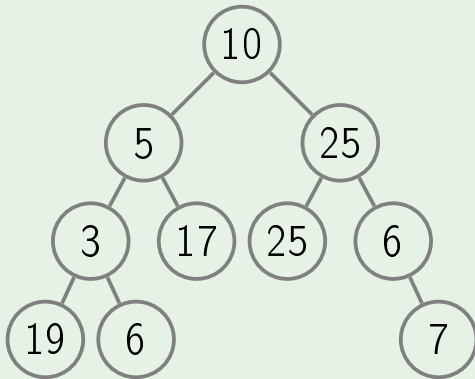
In other words

For each edge of the tree, the value of the parent is at least the value of the child.

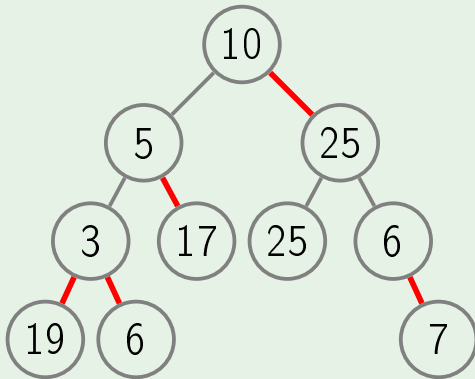
Example: heap



Example: not a heap



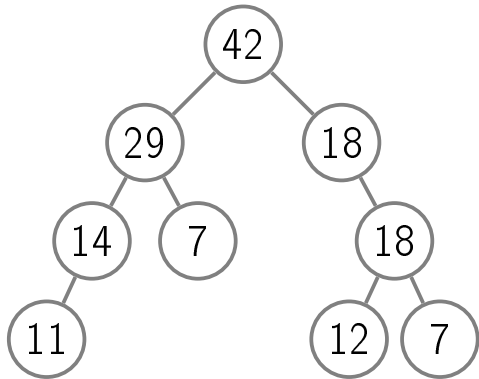
Example: not a heap



Outline

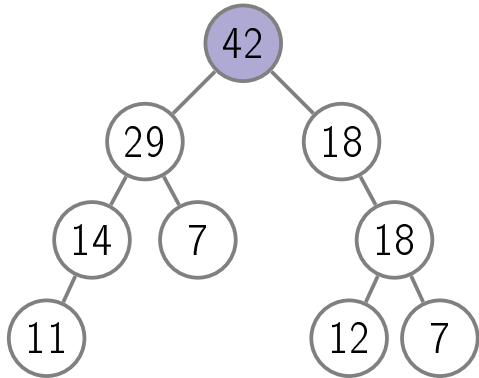
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GetMax



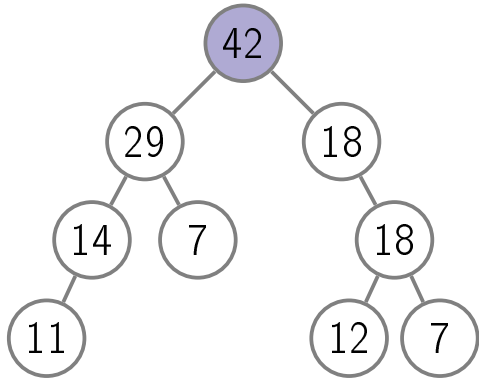
GetMax

return the root
value



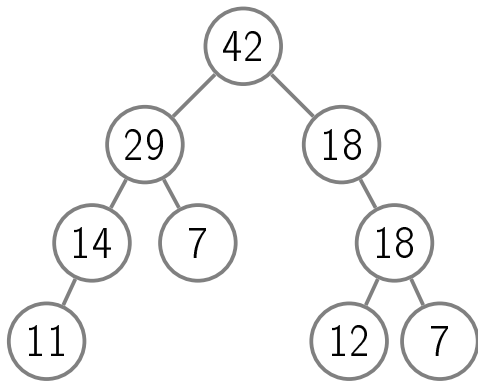
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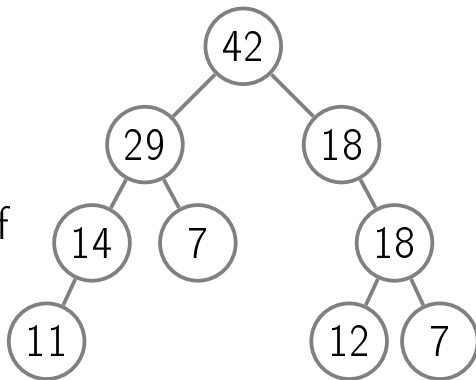
running time: $O(1)$

Insert



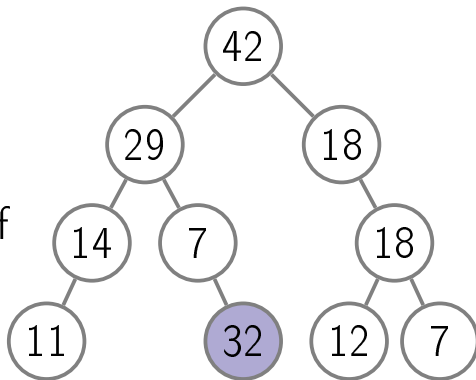
Insert

attach a new
node to any leaf



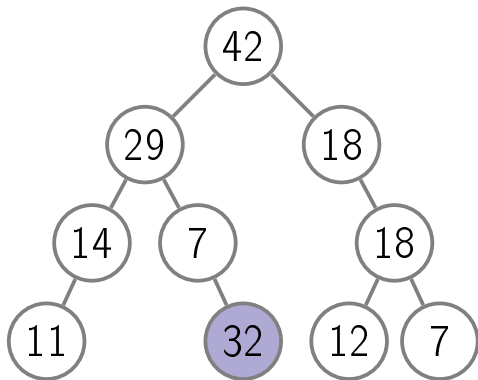
Insert

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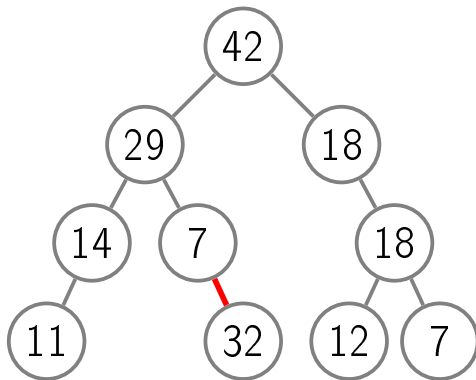
Insert

this may violate
the heap prop-
erty



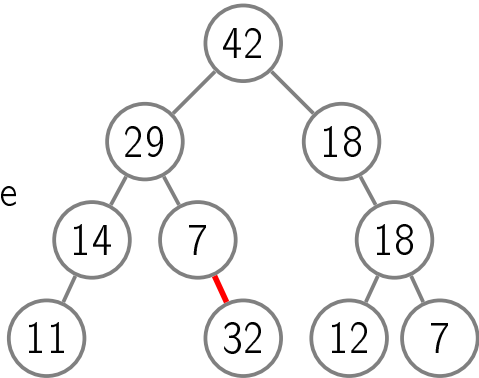
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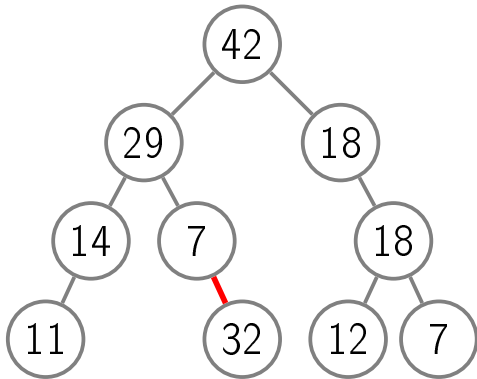
Insert

to fix this, we
let the new node
sift up

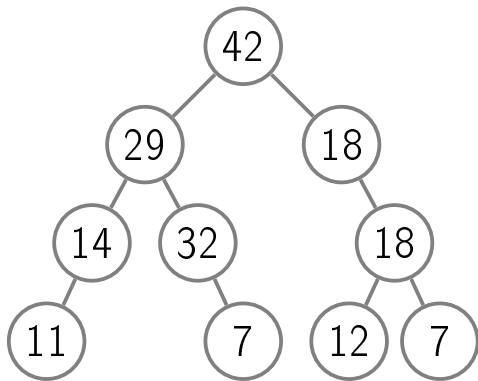


SiftUp

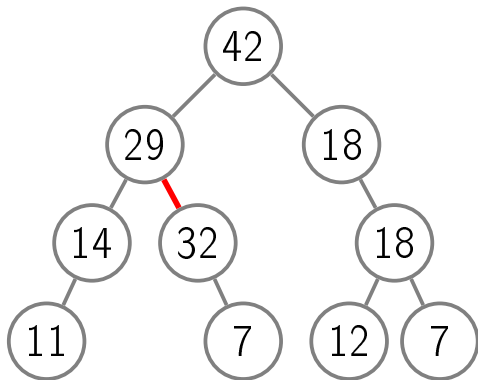
for this, we
swap the prob-
lematic node
with its parent
until the prop-
erty is satisfied



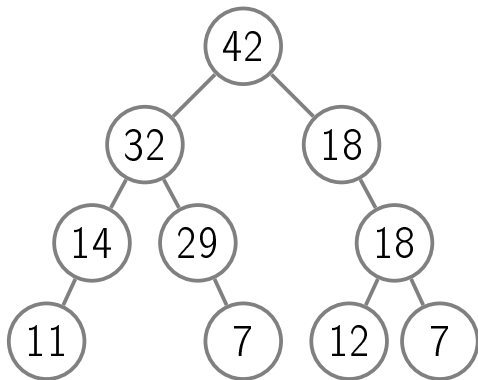
SiftUp



SiftUp

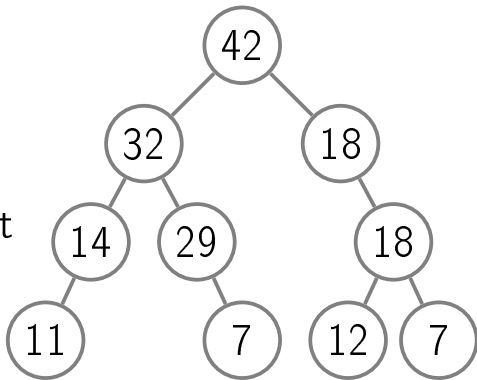


SiftUp



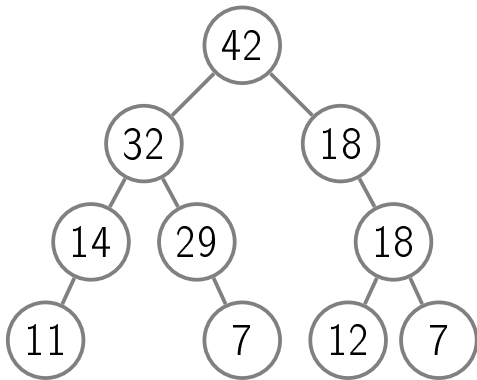
SiftUp

invariant: heap
property is vio-
lated on at most
one edge

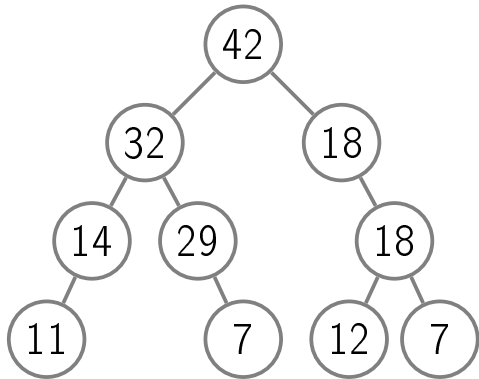


SiftUp

this edge gets
closer to the
root while sift-
ing up

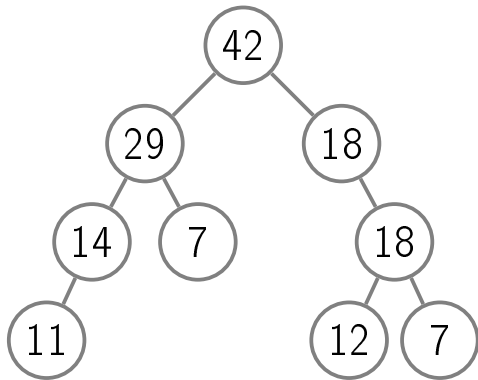


SiftUp



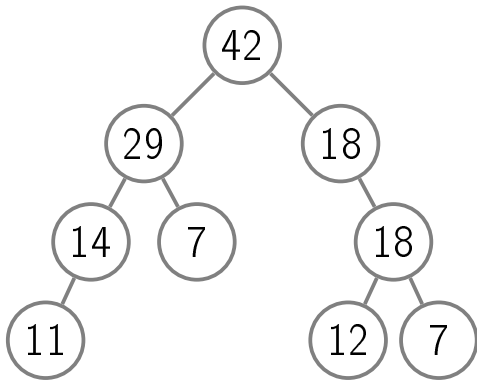
running time: $O(\text{tree height})$

ExtractMax



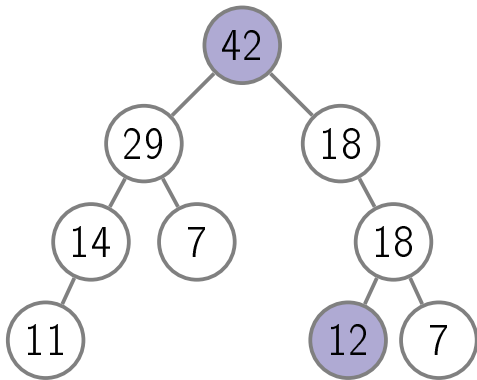
ExtractMax

replace the root
with any leaf



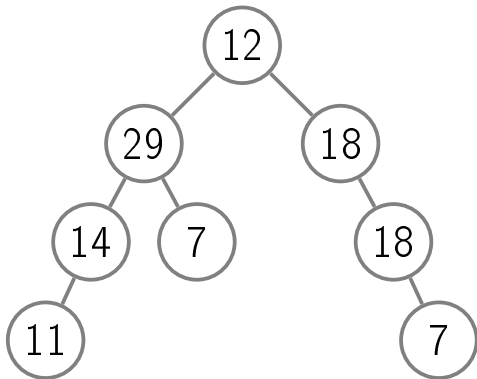
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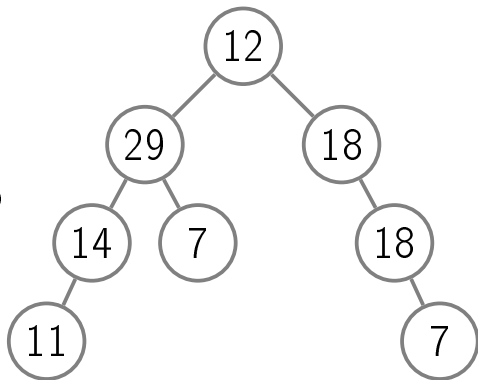
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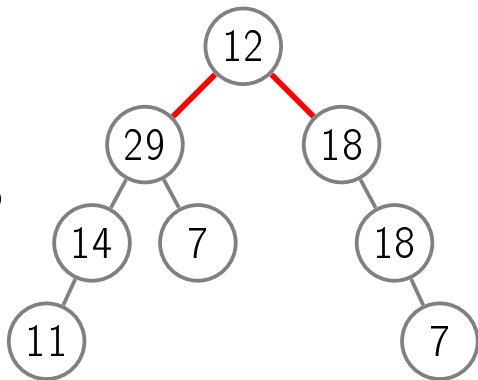
ExtractMax

again, this may
violate the heap
property



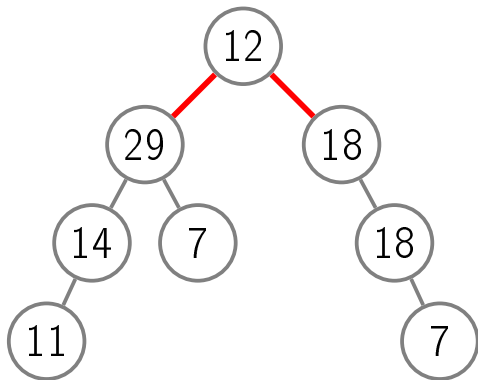
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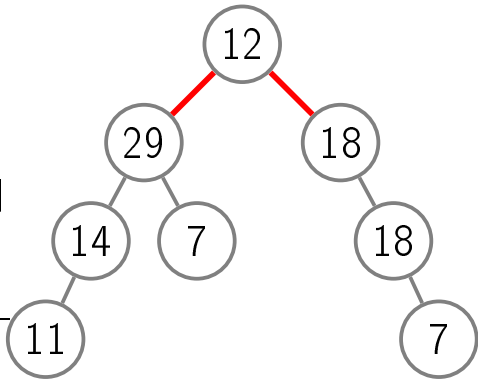
ExtractMax

to fix it, we let
the problematic
node sift down

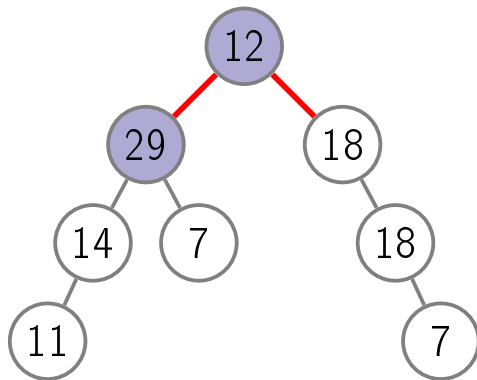


SiftDown

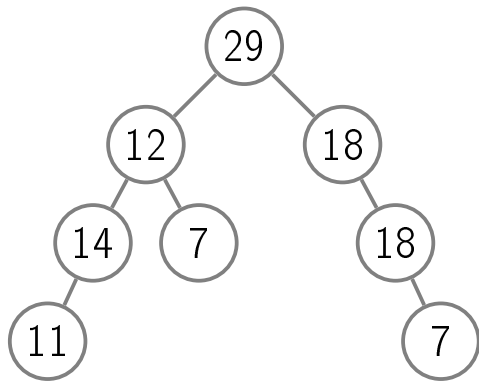
for this, we
swap the prob-
lematic node
with larger child
until the heap
property is satis-
fied



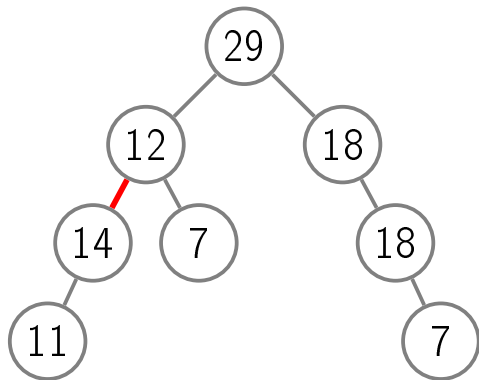
SiftDown



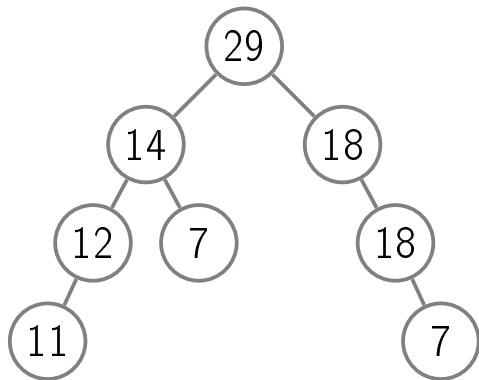
SiftDown



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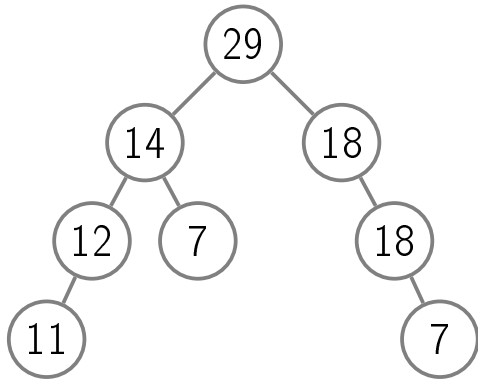


SiftDown

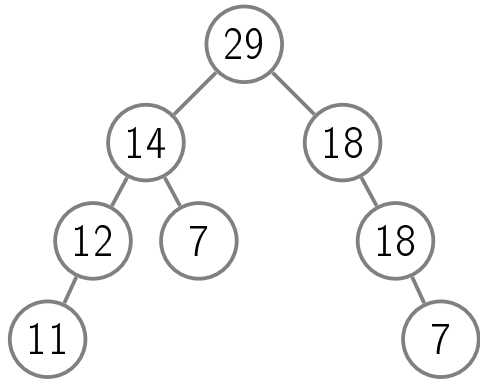


SiftDown

we swap with
the larger child
which automat-
ically fixes one
of the two bad
edges

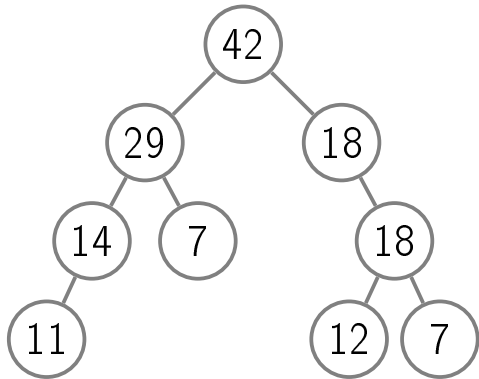


SiftDown



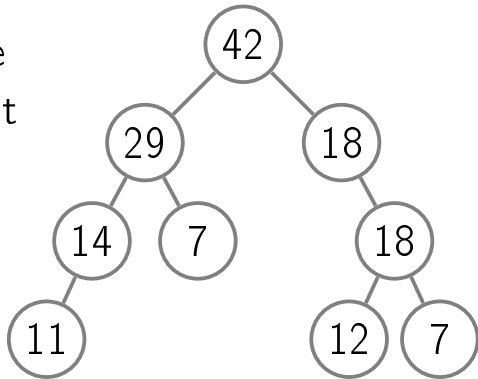
running time: $O(\text{tree height})$

ChangePriority



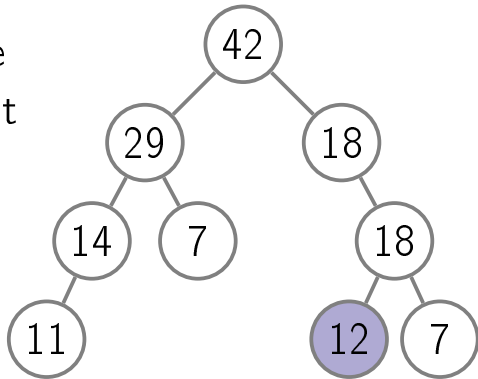
ChangePriority

change the priority and let the changed element sift up or down depending on whether its priority decreased or increased



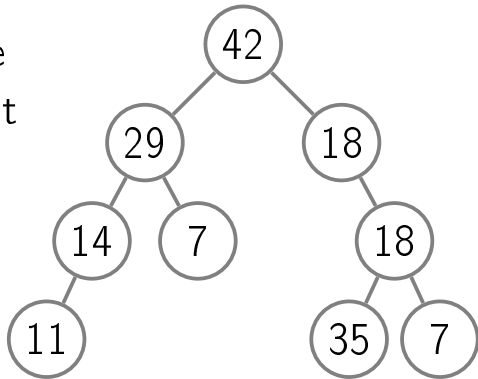
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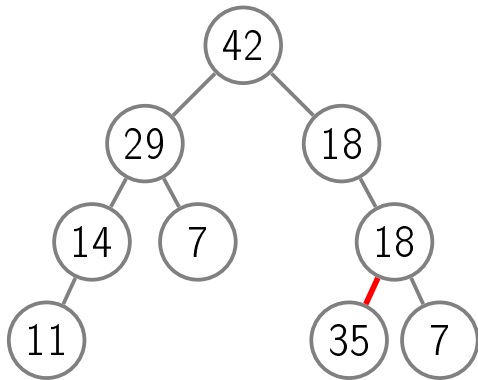


ChangePriority

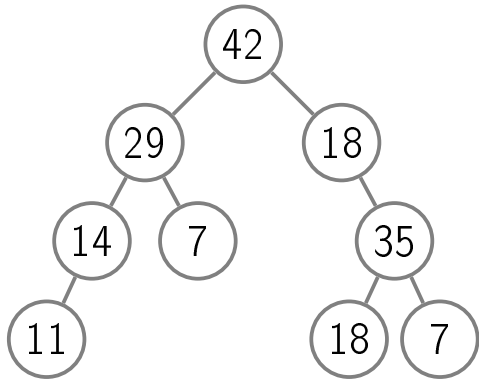
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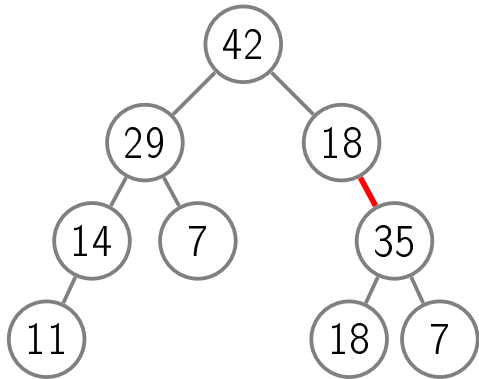
ChangePriority



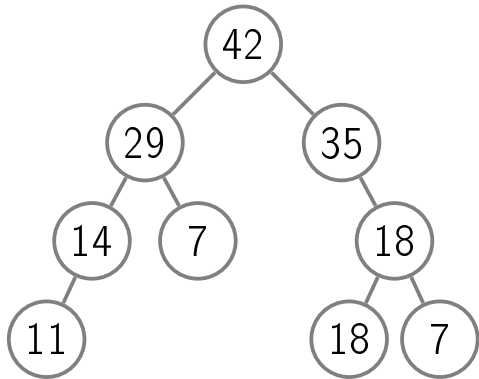
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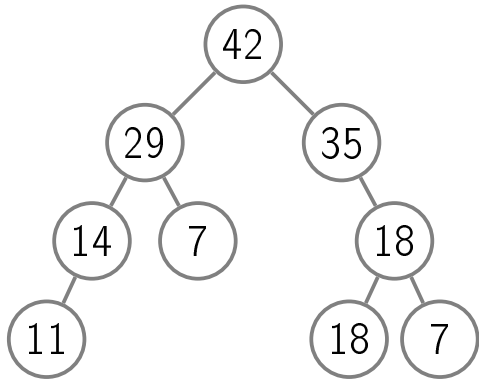
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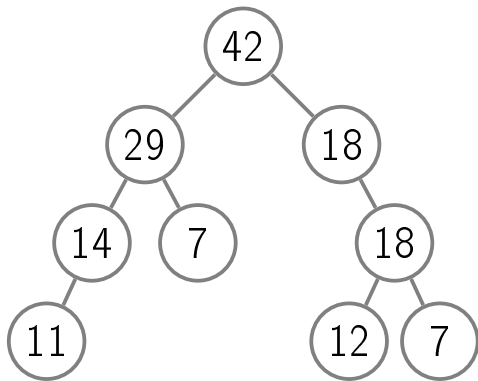


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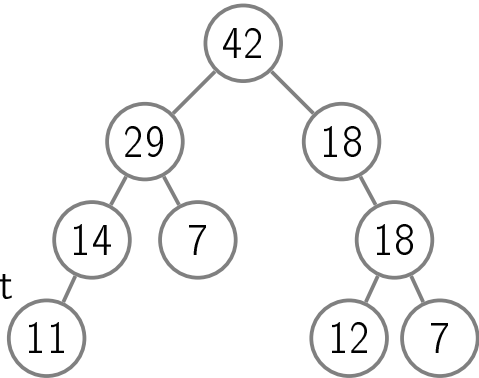
running time: $O(\text{tree height})$

Remove

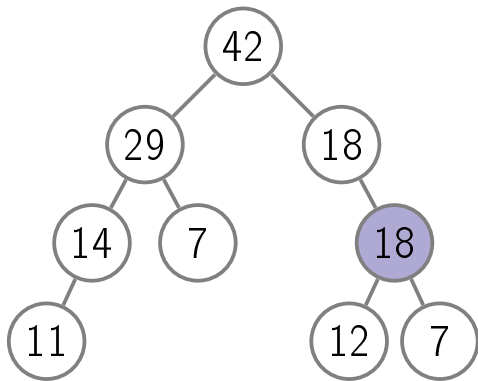


Remove

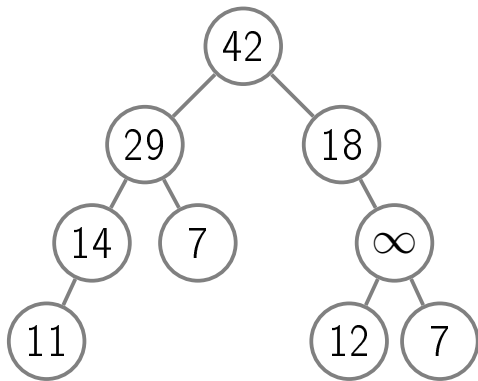
change the priority of the element to ∞ ,
let it sift up,
and then extract maximum



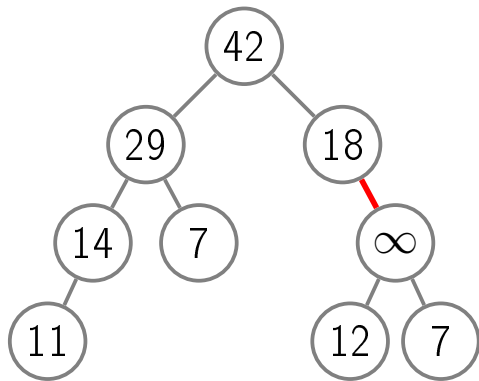
Remove



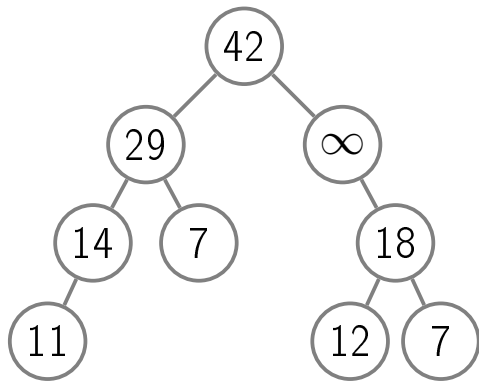
Remove



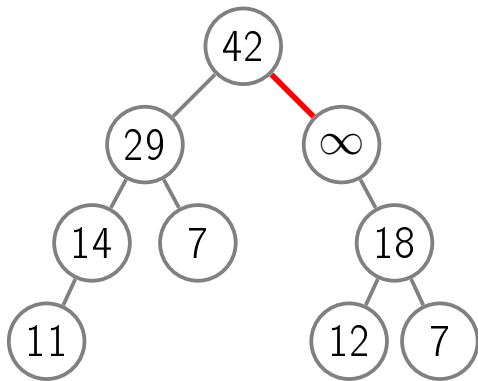
Remove



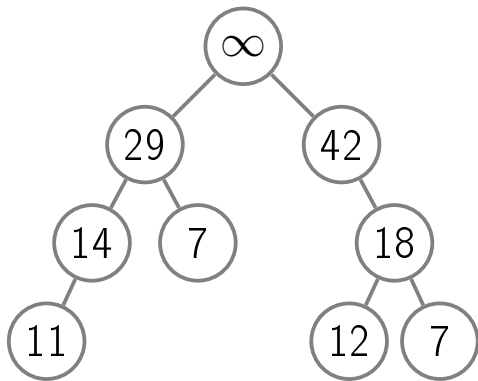
Remove



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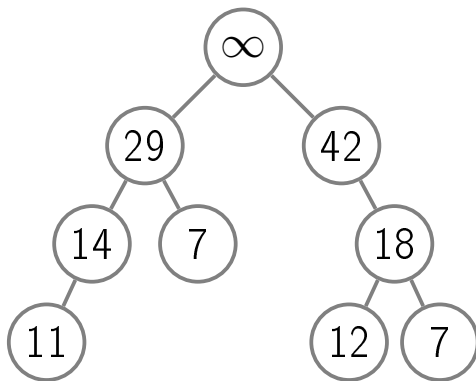


Remove

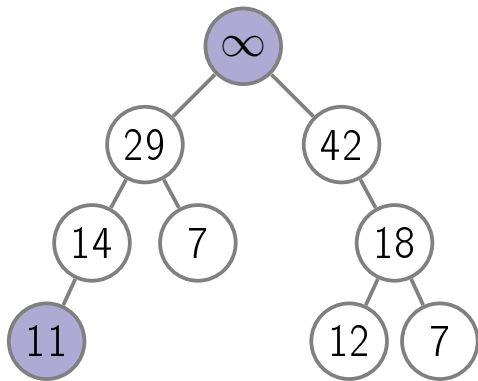


Remove

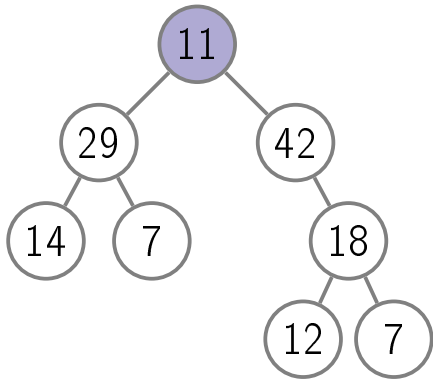
now, call
ExtractMax()



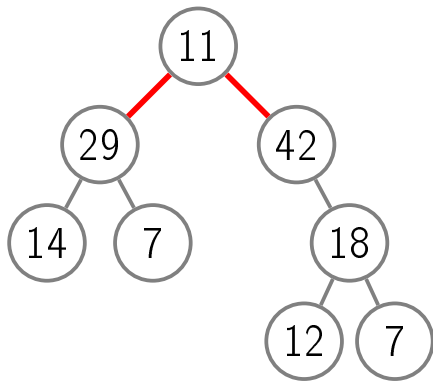
Remove



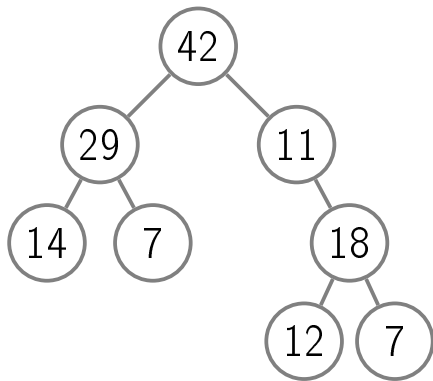
Remove



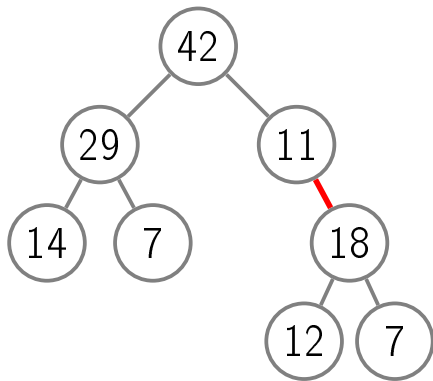
Remove



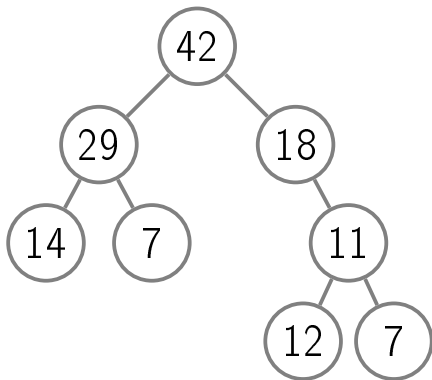
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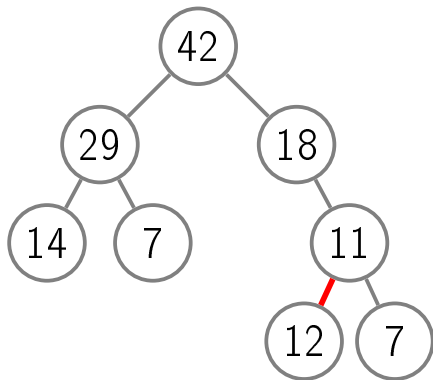
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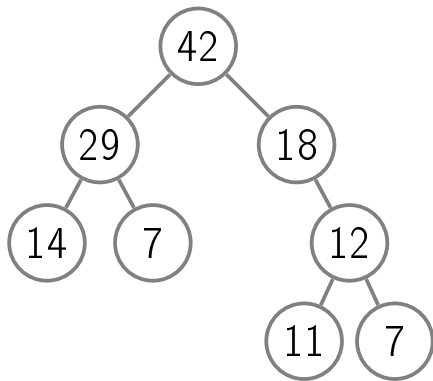
Remove



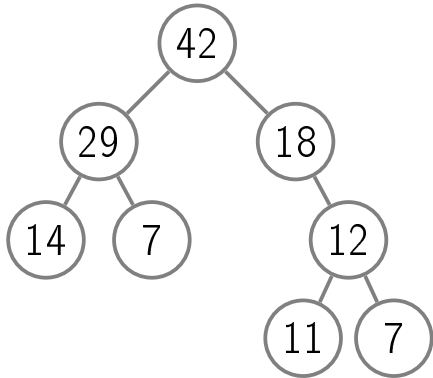
Remove



Remove



Remove



running time: $O(\text{tree height})$

Summary

- GetMax works in time $O(1)$, all other operations work in time $O(\text{tree height})$

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- we definitely want a tree to be shallow

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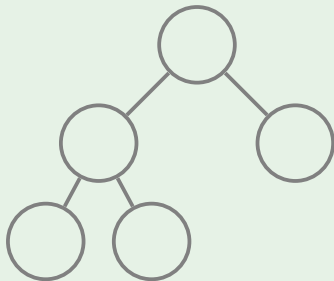
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How to Keep a Tree Shallow?

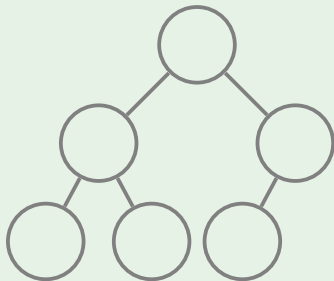
Definition

A binary tree is **complete** if all its levels are filled except possibly the last one which is filled from left to right.

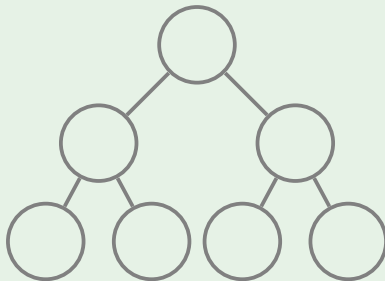
Example: complete binary tree



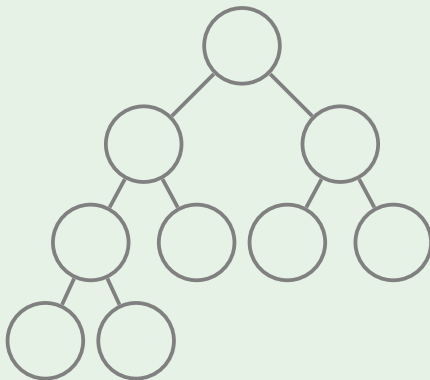
Example: complete binary tree



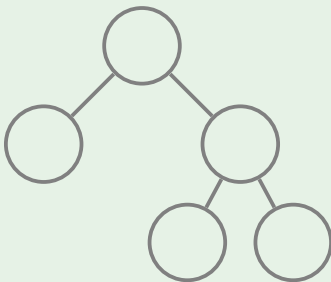
Example: complete binary tree



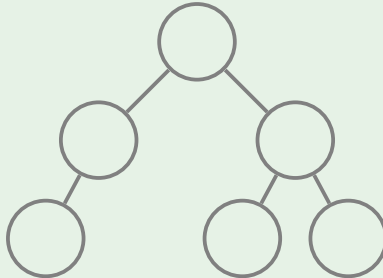
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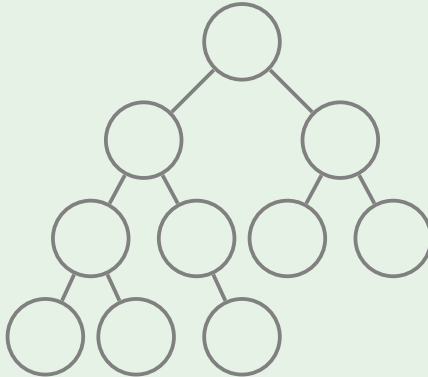
Example: **not** complete binary tree



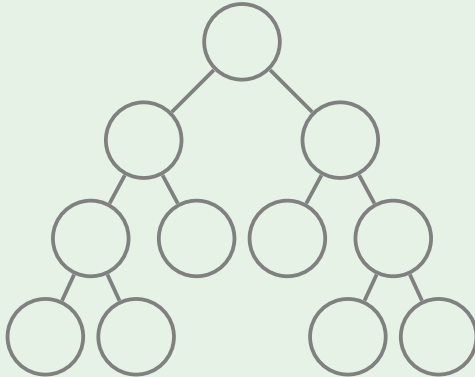
Example: **not** complete binary tree



Example: **not** complete binary tree



Example: **not** complete binary tree



First Advantage: Low Height

Lemma

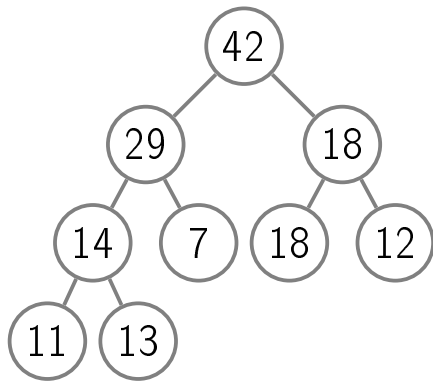
A complete binary tree with n nodes has height at most $O(\log n)$.

Proof

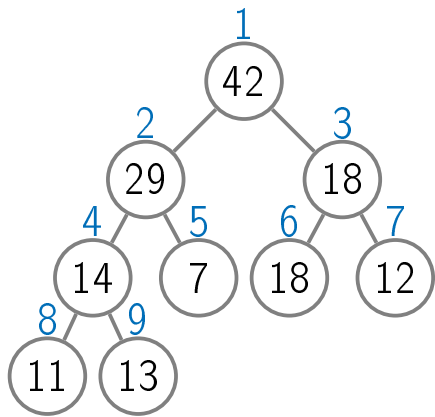
- Complete the last level to get a full binary tree on $n' \geq n$ nodes and the same number of levels ℓ .
- Note that $n' \leq 2n$.
- Then $n' = 2^\ell - 1$ and hence
$$\ell = \log_2(n' + 1) \leq \log_2(2n + 1) = O(\log n).$$



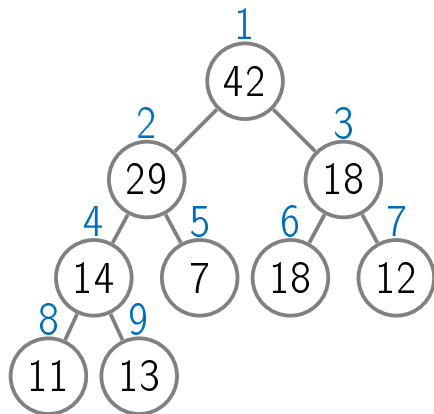
Second Advantage: Store as Array



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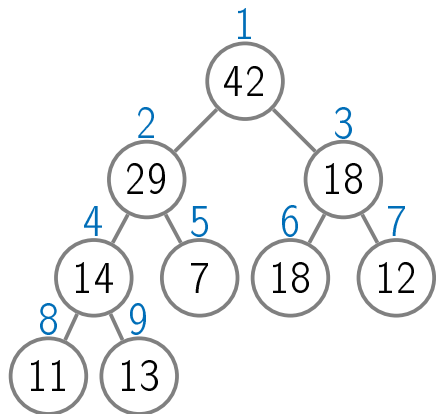


$$\text{parent}(i) = \lfloor \frac{i}{2} \rfloor$$

$$\text{leftchild}(i) = 2i$$

$$\text{rightchild}(i) = 2i + 1$$

Second Advantage: Store as Array



$$\text{parent}(i) = \lfloor \frac{i}{2} \rfloor$$

$$\text{leftchild}(i) = 2i$$

$$\text{rightchild}(i) = 2i + 1$$

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----|----|----|----|---|----|----|----|---|
| 42 | 29 | 18 | 14 | 7 | 18 | 12 | 11 | 5 |

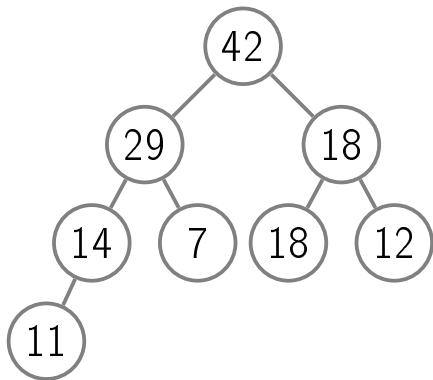
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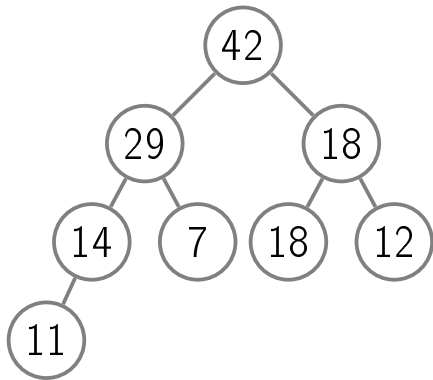
- What do we pay for these advantages?
- We need to keep the tree complete.
- Which binary heap operations modify the shape of the tree?
- Only Insert and ExtractMax (Remove changes the shape by calling ExtractMax).

Keeping the Tree Complete



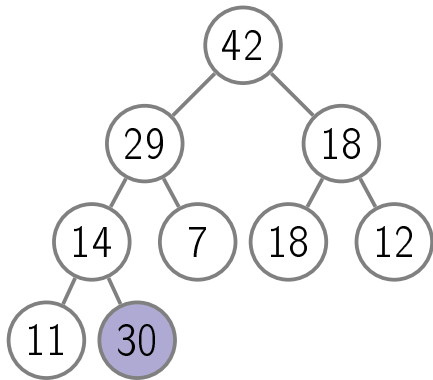
Keeping the Tree Complete

to insert an element, insert it as a leaf in the **leftmost vacant position in the last level** and let it sift up



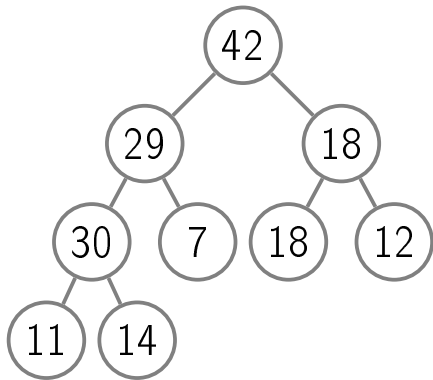
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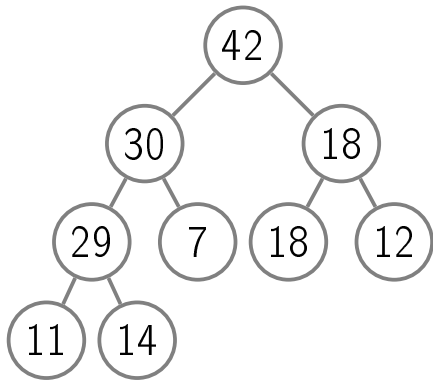
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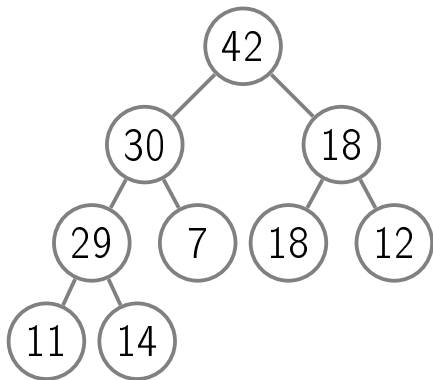
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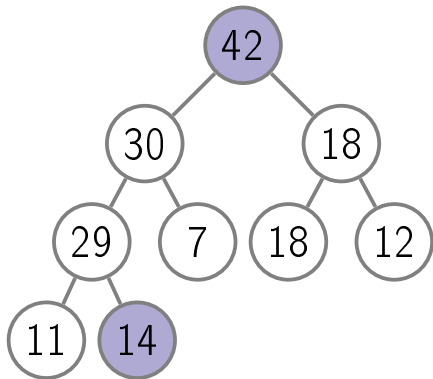
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maximum value,
replace the root
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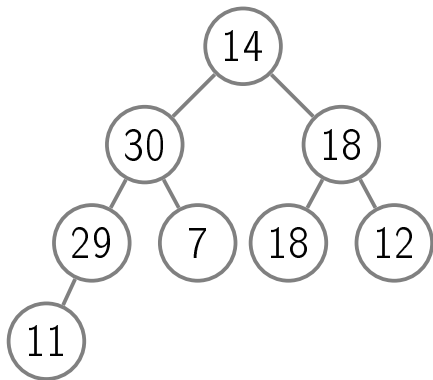
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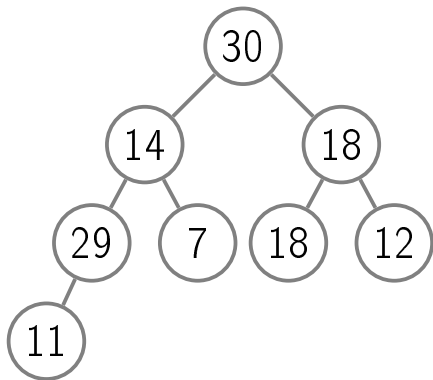
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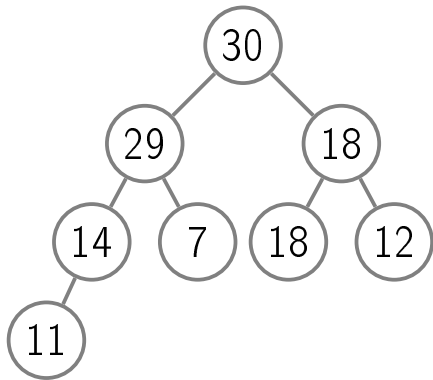
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Outline

- 1 Binary Trees
- 2 Basic Operations
- 3 Complete Binary Trees
- 4 Pseudocode
- 5 Heap Sort
- 6 Final Remarks

General Setting

- *maxSize* is the maximum number of elements in the heap

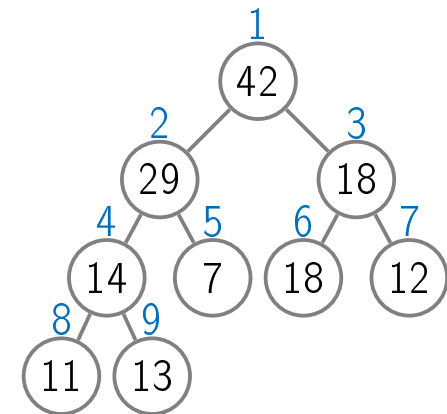
General Setting

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- *size* is the size of the heap

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- *maxSize* is the maximum number of elements in the heap
- *size* is the size of the heap
- $H[1 \dots \textit{maxSize}]$ is an array of length *maxSize* where the heap occupies the first *size* elements

Example



size = 9

maxSize = 13

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|----------|----|----|----|----|---|----|----|----|---|----|----|----|----|
| <i>H</i> | 42 | 29 | 18 | 14 | 7 | 18 | 12 | 11 | 5 | 30 | 29 | 2 | 8 |

Parent(i)

return $\lfloor \frac{i}{2} \rfloor$

LeftChild(i)

return $2i$

RightChild(i)

return $2i + 1$

SiftUp(i)

```
while  $i > 1$  and  $H[\text{Parent}(i)] < H[i]$ :  
    swap  $H[\text{Parent}(i)]$  and  $H[i]$   
     $i \leftarrow \text{Parent}(i)$ 
```


SiftDown(*i*)

$maxIndex \leftarrow i$

$\ell \leftarrow \text{LeftChild}(i)$

if $\ell \leq size$ and $H[\ell] > H[maxIndex]$:

$maxIndex \leftarrow \ell$

$r \leftarrow \text{RightChild}(i)$

if $r \leq size$ and $H[r] > H[maxIndex]$:

$maxIndex \leftarrow r$

if $i \neq maxIndex$:

swap $H[i]$ and $H[maxIndex]$

SiftDown($maxIndex$)

Insert(p)

```
if  $size = maxSize$ :  
    return ERROR  
 $size \leftarrow size + 1$   
 $H[size] \leftarrow p$   
SiftUp( $size$ )
```

ExtractMax()

```
result  $\leftarrow H[1]$   
H[1]  $\leftarrow H[size]$   
size  $\leftarrow size - 1$   
SiftDown(1)  
return result
```

Remove(i)

$H[i] \leftarrow \infty$

SiftUp(i)

ExtractMax()

ChangePriority(i, p)

$oldp \leftarrow H[i]$

$H[i] \leftarrow p$

if $p > oldp$:

 SiftUp(i)

else:

 SiftDown(i)

Summary

The resulting implementation is

- **fast**: all operations work in time $O(\log n)$ (GetMax even works in $O(1)$)

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Summary

The resulting implementation is

- **fast**: all operations work in time $O(\log n)$ (GetMax even works in $O(1)$)
- **space efficient**: we store an array of priorities; parent-child connections are not stored, but are computed on the fly
- **easy to implement**: all operations are implemented in just a few lines of code

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Sort Using Priority Queues

HeapSort($A[1 \dots n]$)

create an empty priority queue

for i from 1 to n :

 Insert($A[i]$)

for i from n downto 1:

$A[i] \leftarrow \text{ExtractMax}()$

- The resulting algorithm is comparison-based and has running time $O(n \log n)$ (hence, asymptotically optimal!).

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- Natural generalization of selection sort: instead of simply scanning the rest of the array to find the maximum value, use a smart data structure.
- Not in-place: uses additional space to store the priority queue.

This lesson

In-place heap sort algorithm. For this, we will first turn a given array into a heap by permuting its elements.

Turn Array into a Heap

BuildHeap($A[1 \dots n]$)

$size \leftarrow n$

for i from $\lfloor n/2 \rfloor$ downto 1:
 SiftDown(i)

- We repair the heap property going from bottom to top.

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- [Online visualization](#)
- Running time: $O(n \log n)$

In-place Heap Sort

HeapSort($A[1 \dots n]$)

BuildHeap(A) $\{size = n\}$

repeat $(n - 1)$ times:

 swap $A[1]$ and $A[size]$

$size \leftarrow size - 1$

 SiftDown(1)

Building Running Time

- The running time of BuildHeap is $O(n \log n)$ since we call SiftDown for $O(n)$ nodes.

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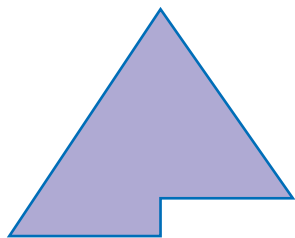
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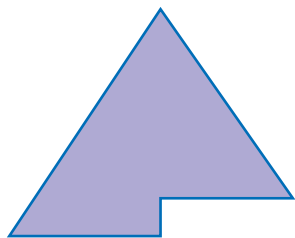
- The running time of BuildHeap is $O(n \log n)$ since we call SiftDown for $O(n)$ nodes.
- If a node is already close to the leaves, then sifting it down is fast.
- We have many such nodes!
- Was our estimate of the running time of BuildHeap too pessimistic?

Building Running Time



| # nodes | $T(\text{SiftDown})$ |
|------------|----------------------|
| 1 | $\log_2 n$ |
| 2 | |
| \vdots | \vdots |
| $\leq n/4$ | 2 |
| $\leq n/2$ | 1 |

Building Running Time



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| 2 | |
| \vdots | \vdots |
| $\leq n/4$ | 2 |
| $\leq n/2$ | 1 |

$$\begin{aligned}T(\text{BuildHeap}) &\leq \frac{n}{2} \cdot 1 + \frac{n}{4} \cdot 2 + \frac{n}{8} \cdot 3 + \dots \\&\leq n \cdot \sum_{i=1}^{\infty} \frac{i}{2^i} = 2n\end{aligned}$$

Estimating the Sum

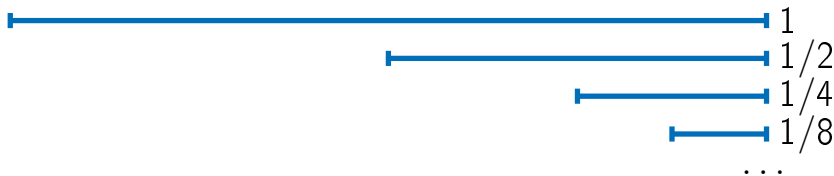


$$\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \dots = \sum_{k=1}^{\infty} \frac{1}{2^k} = 1$$

Estimating the Sum



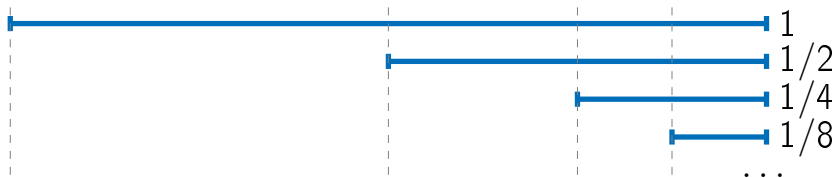
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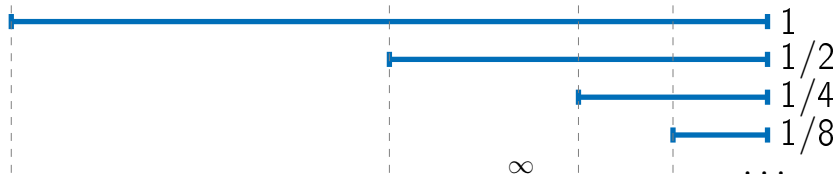
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$$\frac{1}{2} + \frac{2}{4} + \frac{3}{8} + \frac{4}{16} + \dots = \sum_{k=1}^{\infty} \frac{k}{2^k} = 2$$

Partial sorting

Input: An array $A[1 \dots n]$, an integer $1 \leq k \leq n$.

Output: The last k elements of a sorted version of A .

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Can be solved in $O(n)$ if $k = O(\frac{n}{\log n})!$

PartialSorting($A[1 \dots n], k$)

BuildHeap(A)

for i from 1 to k :

 ExtractMax()

PartialSorting($A[1 \dots n], k$)

BuildHeap(A)

for i from 1 to k :

 ExtractMax()

Running time: $O(n + k \log n)$

Summary

Heap sort is a time and space efficient comparison-based algorithm: has running time $O(n \log n)$, uses no additional space.

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0-based Arrays

Parent(i)

return $\lfloor \frac{i-1}{2} \rfloor$

LeftChild(i)

return $2i + 1$

RightChild(i)

return $2i + 2$

Binary Min-Heap

Definition

Binary **min**-heap is a binary tree (each node has zero, one, or two children) where the value of each node is **at most** the values of its children.

Can be implemented similarly.

d -ary Heap

- In a d -ary heap nodes on all levels except for possibly the last one have exactly d children.

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- In a d -ary heap nodes on all levels except for possibly the last one have exactly d children.
- The height of such a tree is about $\log_d n$.
- The running time of SiftUp is $O(\log_d n)$.
- The running time of SiftDown is $O(d \log_d n)$: on each level, we find the largest value among d children.

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Summary

- Priority queue supports two main operations: Insert and ExtractMax.
- In an array/list implementation one operation is very fast ($O(1)$) but the other one is very slow ($O(n)$).
- Binary heap gives an implementation where both operations take $O(\log n)$ time.
- Can be made also space efficient.