# Data Structures

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Realdolmen

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# Who am I?

- Master of Engineering: Computer Science (KUL)
  - Computational informatics
- Realdolmen: acADDemICT in 09/2015
- Current project: Planning infrastructure @ Infrabel

# Outline

1. Introductory Data Structures
   - Array
   - Linked List
   - Hash Table
   - Tree
2. Java Collection API & Map API
   - Java Collection API
   - Java Map API
3. Advanced Data Structures
   - Bloom Filter
   - Rope
   - Skiplist
   - Merkle Tree
   - Union Find
   - Treap

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# What are Data Structures?

## Data Structure[1]

A way in which data are stored for efficient search and retrieval. Different data structures are suited for different problems.

- Data type $\neq$ data structure
- `java.util.HashSet` vs. hash table
- `array` vs. array

[1] Encyclopædia Britannica

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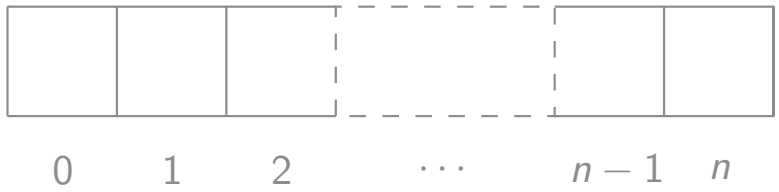
# Array

## Definition

- An indexed set of related elements.[2]
- An assemblage of items that are randomly accessible by integers, the index.[3]

- Example: linear array




[2] Oxford Dictionary
[3] National Institute of Standards & Technology

# Array

## Operations

- `get`
- `set`
- `indexOf`

# Array

## Operations

- `get`
- `set`
- `indexOf`

`get(1)`

# Array

## Operations

- `get`
- `set`
- `indexOf`

`get(1)`

# Array

## Operations

- `get` $O(1)$
- `set`
- `indexOf`

`get(1)`

# Array

## Operations

- `get` $O(1)$
- `set`
- `indexOf`

`set(2)`

# Array

## Operations

- `get` $O(1)$
- `set`
- `indexOf`

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# Array

## Operations

- `get` $O(1)$
- `set` $O(1)$
- `indexOf`

`set(2)`

# Array

## Operations

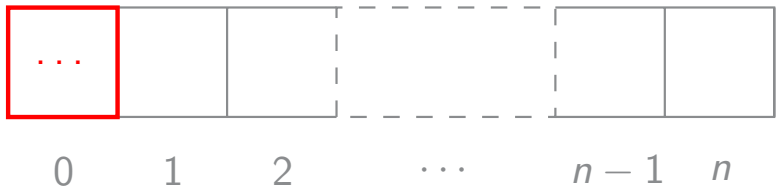
- `get` $O(1)$
- `set` $O(1)$
- `indexOf`

`indexOf(object)`

# Array

## Operations

- `get` $O(1)$
- `set` $O(1)$
- `indexOf`




`indexOf(object)`

# Array

## Operations

- `get` $O(1)$
- `set` $O(1)$
- `indexOf`

`indexOf(object)`

# Array

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- `get` $O(1)$
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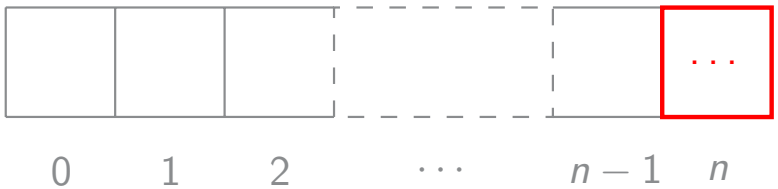


`indexOf(object)`

# Array

## Operations

- `get` $O(1)$
- `set` $O(1)$
- `indexOf` $O(n)$

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# Linked List

## Definition

A linked list is a data structure in which the objects are arranged in a linear order. Unlike arrays in which the linear order is determined by indices, the order is determined by a pointer in each object.[4]

- Different types: singly, doubly, multiply, circular, ...
- Example: doubly linked list

[4] Introduction to Algorithms By Cormen, Leierson, Rivest & Stein

# Linked List

## Operations

- `add/remove first/last`
- `get/insertAt`
- `indexOf`

# Linked List

## Operations

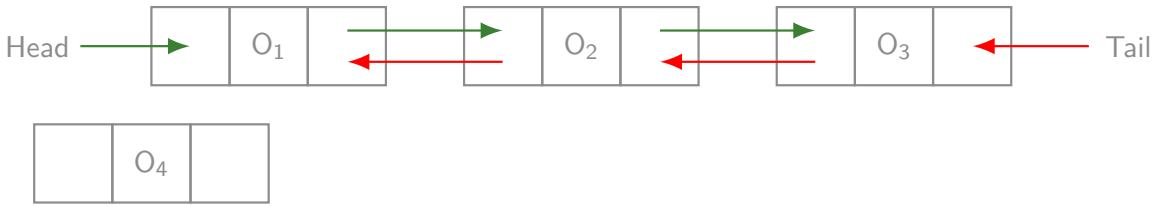
- `add/remove first/last`
- `get/insertAt`
- `indexOf`

`addFirst(`$O_4$`)`

# Linked List

## Operations

- `add/remove first/last`
- `get/insertAt`
- `indexOf`

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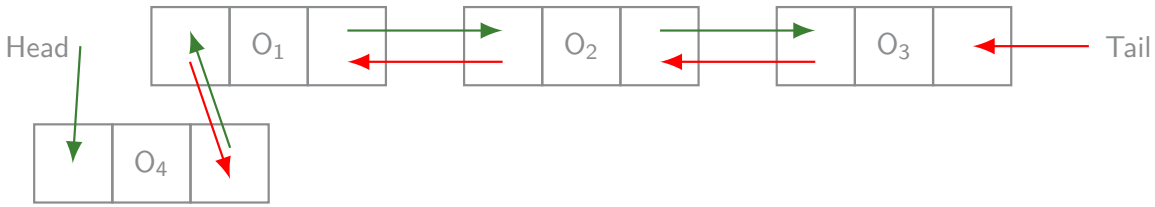


`addFirst(`$O_4$`)`

# Linked List

## Operations

- `add/remove first/last` $O(1)$
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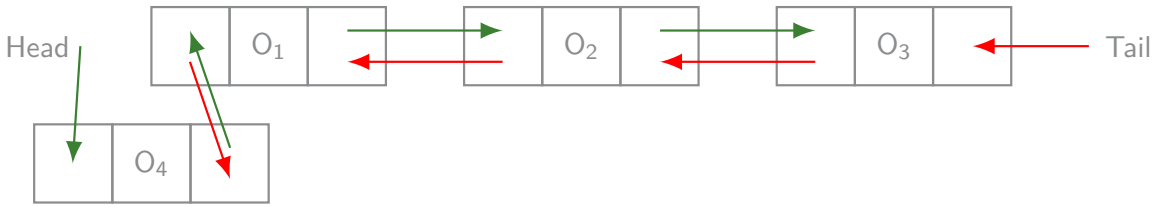
- `indexOf`




`addFirst(`$O_4$`)`

# Linked List

## Operations

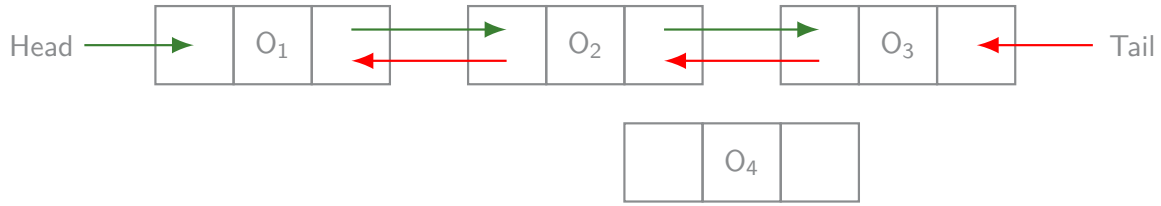
- `add/remove first/last` $O(1)$
- `get/insertAt`
- `indexOf`

`insertAt(2)`

# Linked List

## Operations

- `add/remove first/last` $O(1)$
- `get/insertAt`
- `indexOf`




`insertAt(2)`

# Linked List

## Operations

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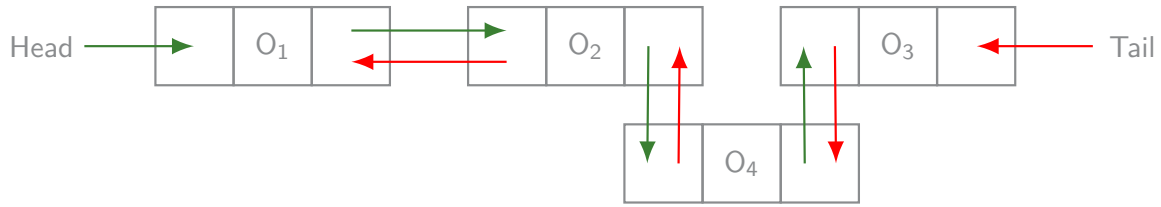
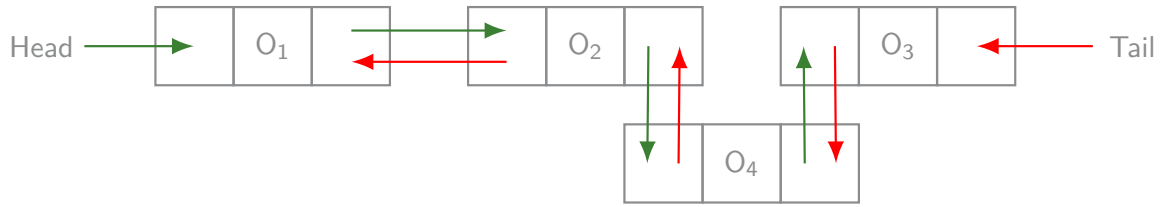



`insertAt(2)`

# Linked List

## Operations

- `add/remove first/last` $O(1)$
- `get/insertAt` $O(n)$
- `indexOf`




`insertAt(2)`

# Linked List

## Operations

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- `get/insertAt` $O(n)$
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`indexOf(`$O_2$`)`

# Linked List

## Operations

- `add/remove first/last` $O(1)$
- `get/insertAt` $O(n)$
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`indexOf(`$O_2$`)`

# Linked List

## Operations

- `add/remove first/last` $O(1)$
- `get/insertAt` $O(n)$
- `indexOf`

`indexOf(`$O_2$`)`

# Linked List

## Operations

- `add/remove first/last` $O(1)$
- `get/insertAt` $O(n)$
- `indexOf` $O(n)$

`indexOf`$(O_2)$

# Linked List

## Operations

- `add/remove first/last` $O(1)$
- `get/insertAt` $O(n)$
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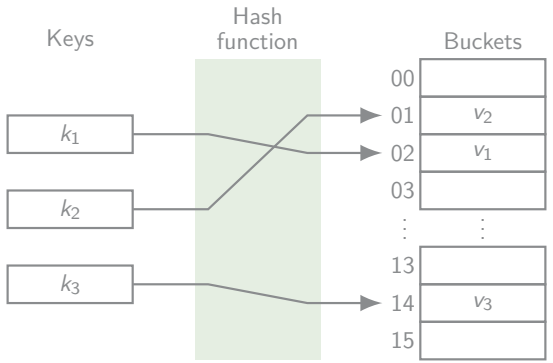
# Hash Table

## Definition

A dictionary in which keys are mapped to array positions by hash functions.[5]

- Hash functions: determinism, uniformity, defined range, data normalisation, non-invertible, perfect, ...
- Collisions resolution: chaining, open addressing, ...
- Example:

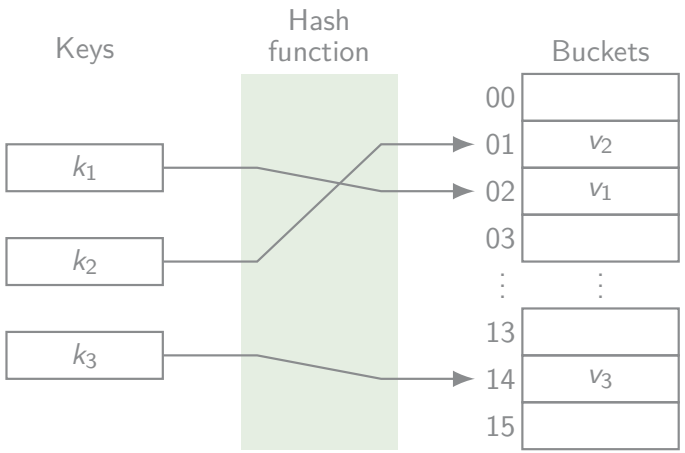



[5] National Institute of Standards & Technology

# Hash Table

## Operations

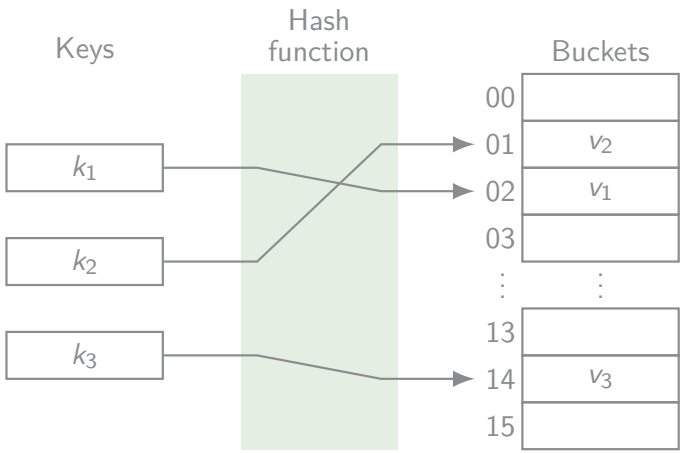
- `put`
- `remove`
- `get`



# Hash Table

## Operations

- `put`
- `remove`
- `get`

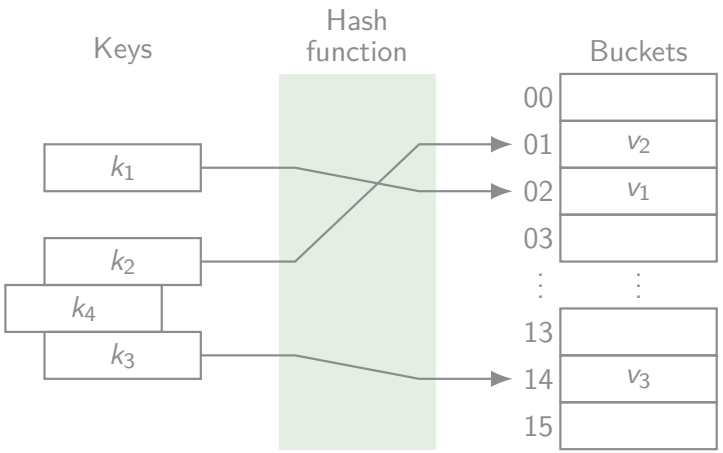



`put(O4)`

# Hash Table

## Operations

- `put`
- `remove`
- `get`




`put(O4)`

# Hash Table

## Operations

- `put`
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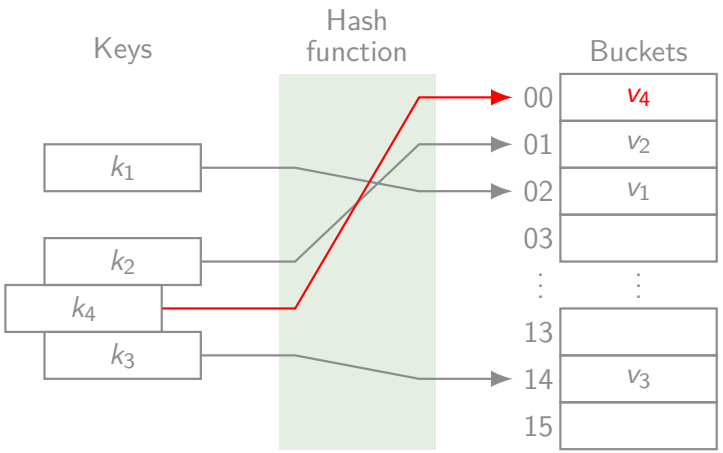
- `get`

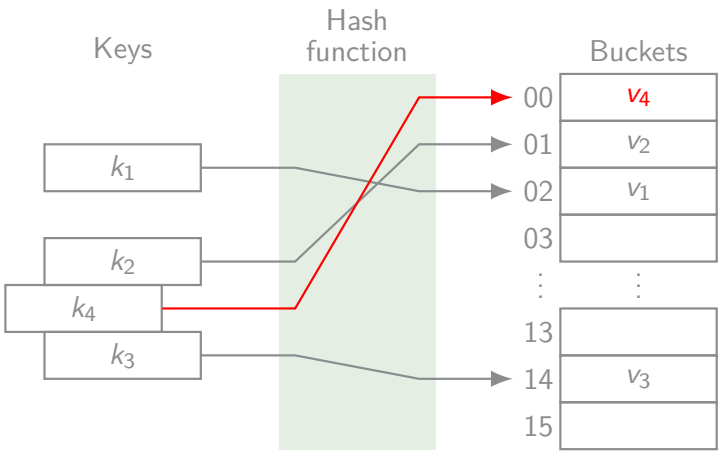



`put(O4)`

# Hash Table

## Operations

- `put` $O(1)$ / $O(n)$
- `remove`
- `get`




`put(`$O_4$`)`

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## Operations

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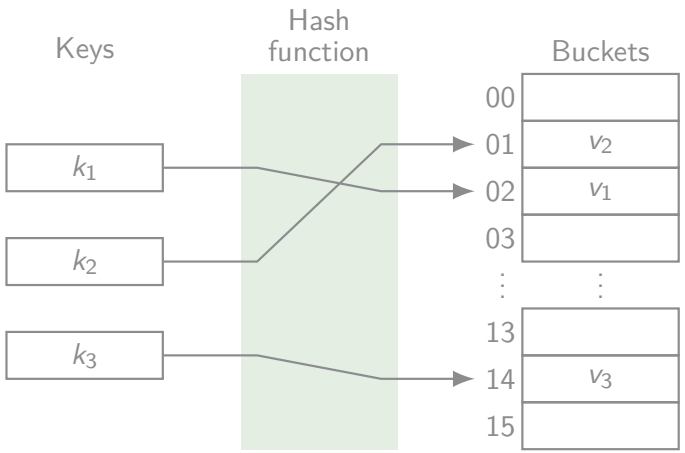
- `get`

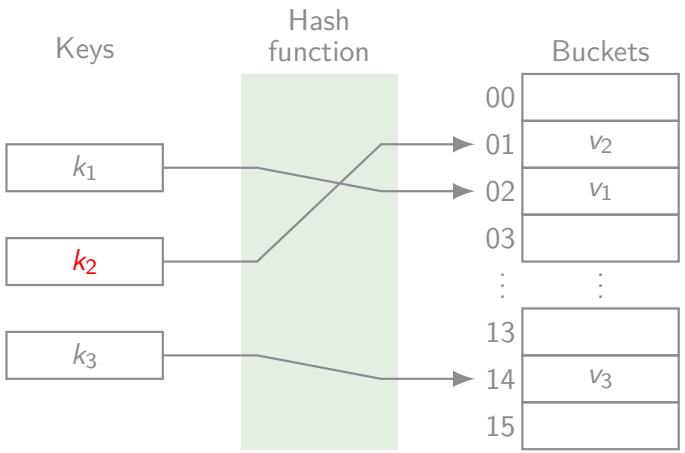



`remove(`$O_2$`)`

# Hash Table

## Operations

- `put` $O(1)$ / $O(n)$
- `remove`
- `get`

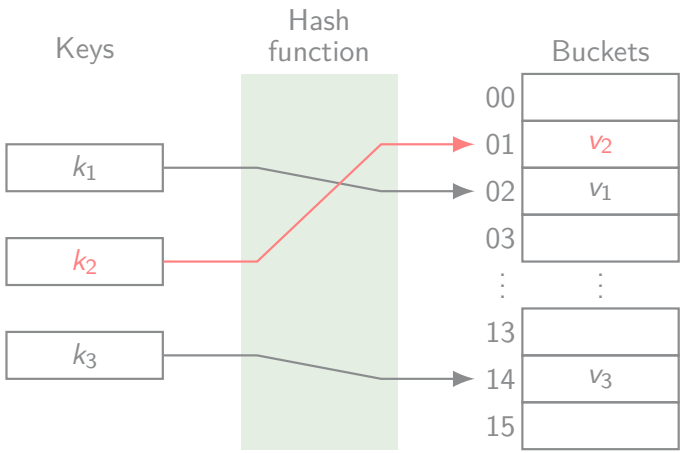



`remove(`$O_2$`)`

# Hash Table

## Operations

- `put` $O(1)$ / $O(n)$
- `remove`
- `get`

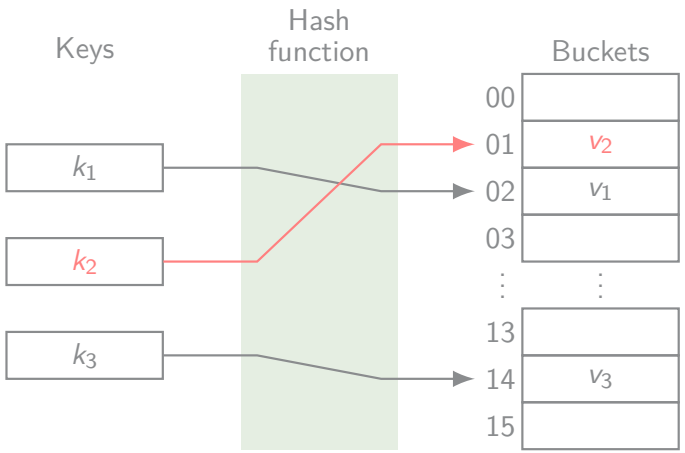



`remove(`$O_2$`)`

# Hash Table

## Operations

- `put` $O(1)$ / $O(n)$
- `remove` $O(1)$ / $O(n)$
- `get`

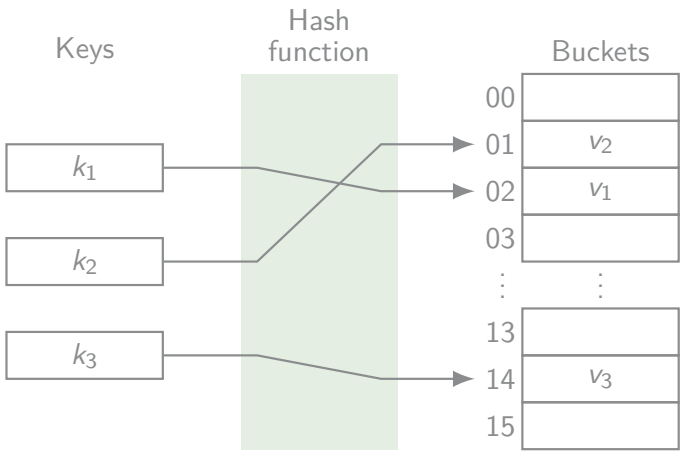



`remove`$(0_2)$

# Hash Table

## Operations

- `put` $O(1)$ / $O(n)$
- `remove` $O(1)$ / $O(n)$
- `get`




`get(`$O_2$`)`

# Hash Table

## Operations

- `put` $O(1)$ / $O(n)$
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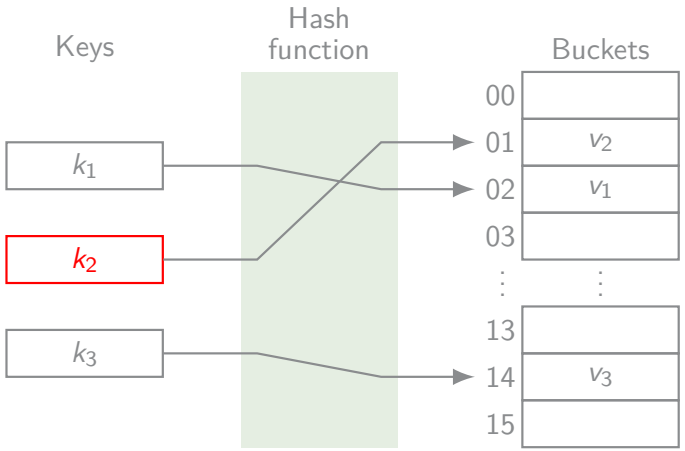


`get(`$O_2$`)`

# Hash Table

## Operations

- `put` $O(1)$ / $O(n)$
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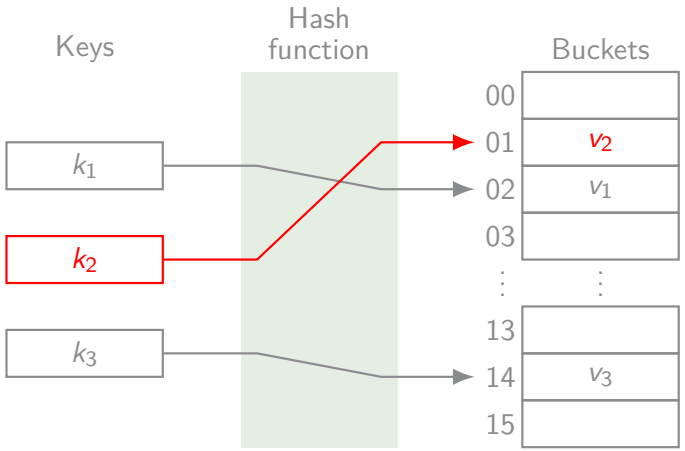
- `get`




`get(O2)`

# Hash Table

## Operations

- `put` $O(1)$ / $O(n)$
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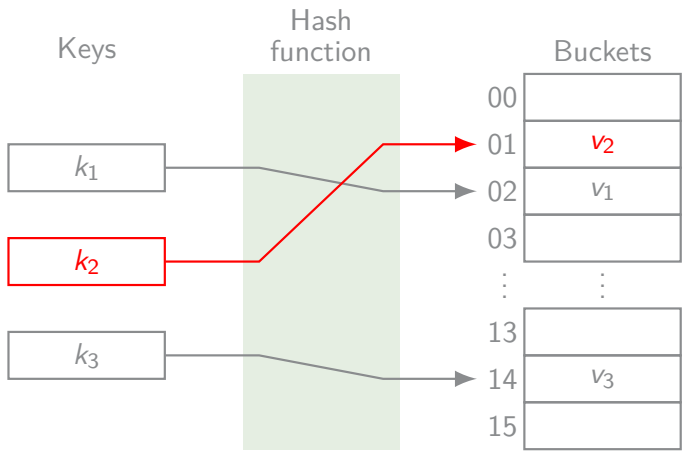


`get`$(O_2)$

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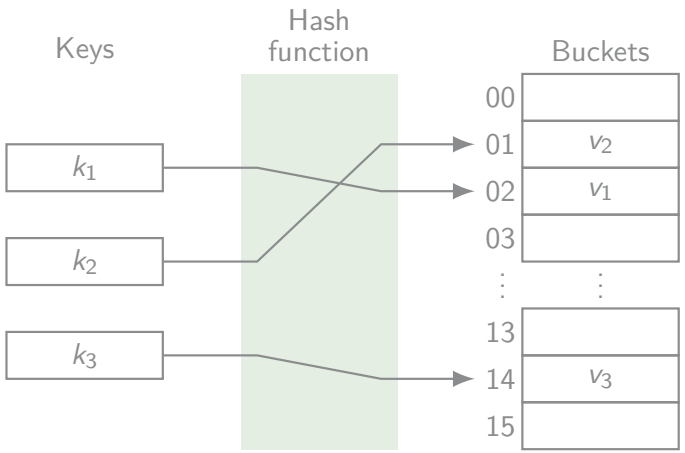

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     - Heap
     - Binary Search Tree
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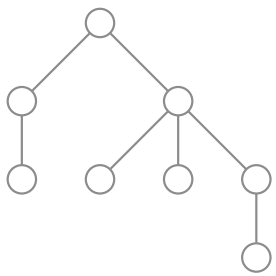
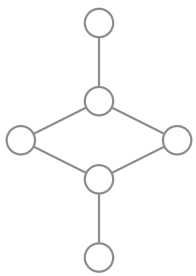
# Tree

## Definition

A data structure made up of nodes or vertices and edges without having any cycle. A tree that is not empty consists of a root node and potentially many levels of additional nodes that form a hierarchy.

- Depth, binary, (nearly) complete, ...
- Example:





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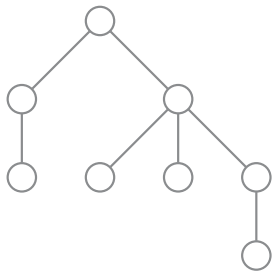
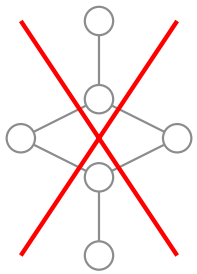




# Binary Heap

## Definition (Heap)

A complete tree where every node has a key more extreme (greater or less) than or equal to the key of its parent.[6]

## Definition (Binary Heap)

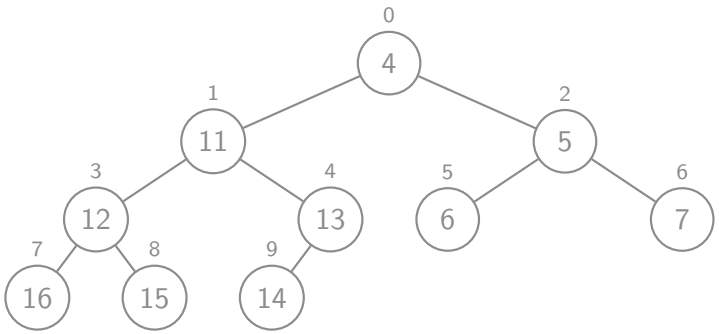
A binary heap data structure is an array object that we can view as a nearly complete binary tree that satisfies the min-heap or max-heap property.[7]

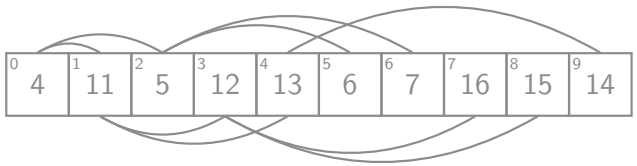
[6] National Institute of Standards & Technology

[7] Introduction to Algorithms By Cormen, Leierson, Rivest & Stein

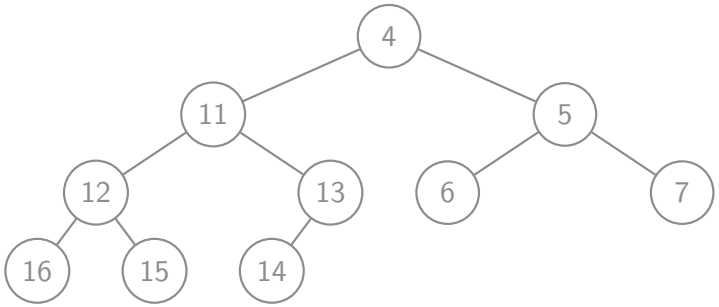
# Binary Min-Heap

- `Parent(n)` $\lfloor \frac{n-1}{2} \rfloor$
- `Left(n)` $2n+1$
- `Right(n)` $2(n+1)$



# Binary Min-Heap



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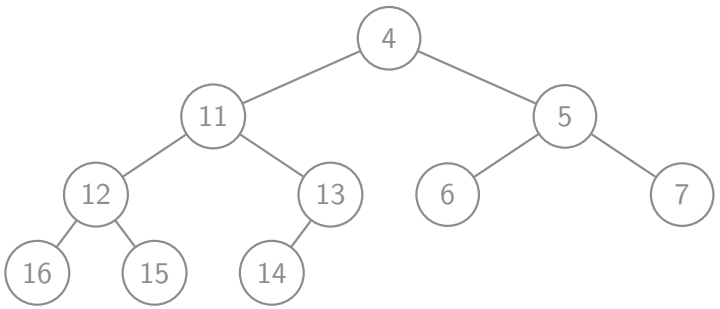
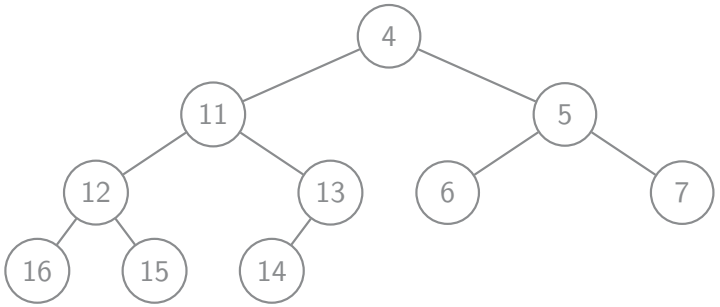
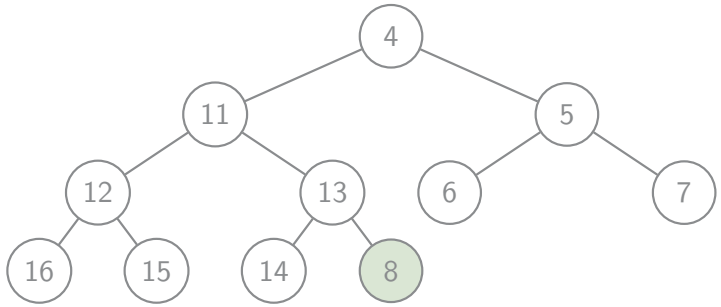



add 8

# Binary Min-Heap



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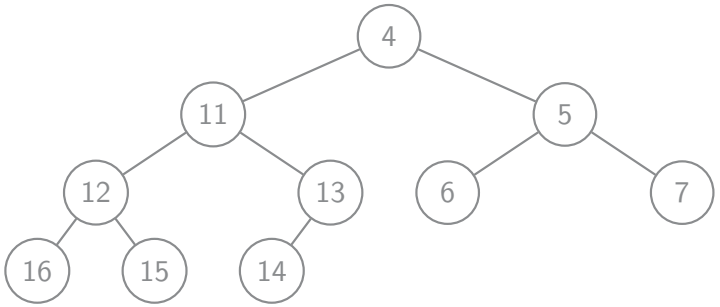


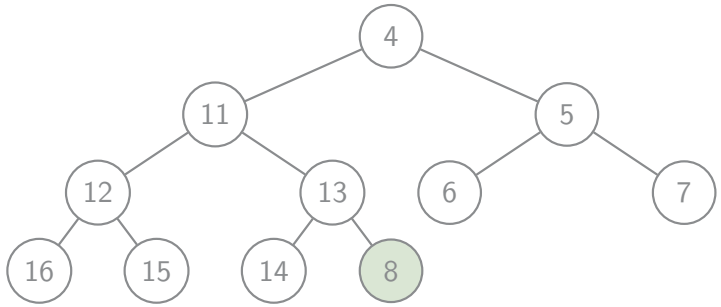


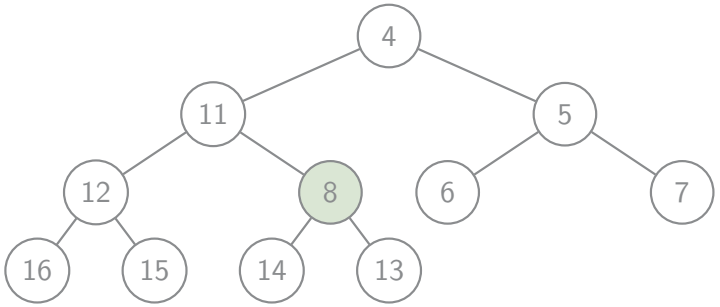

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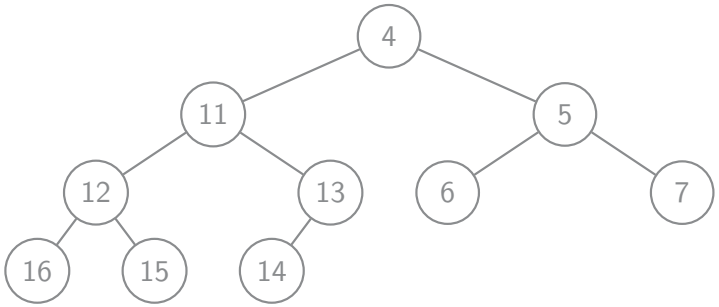


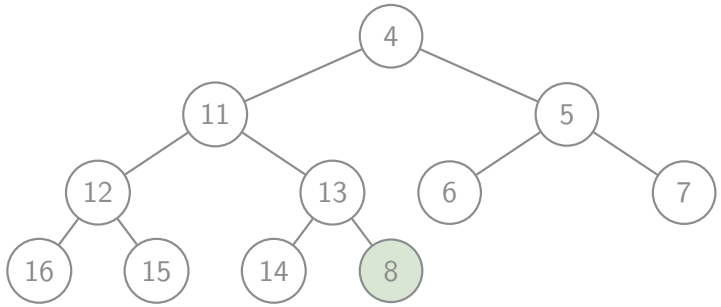


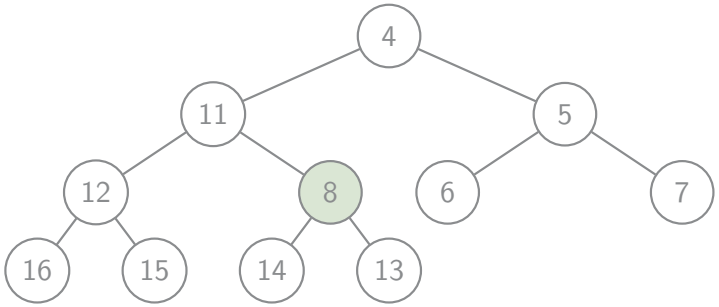


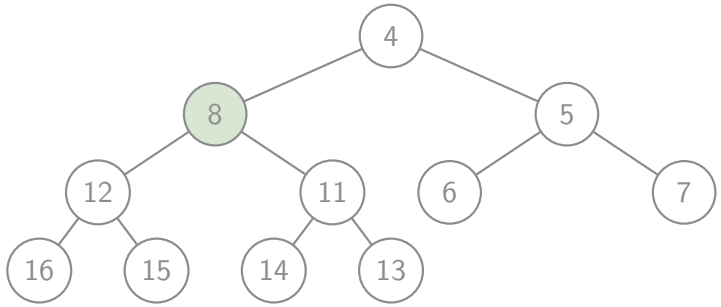

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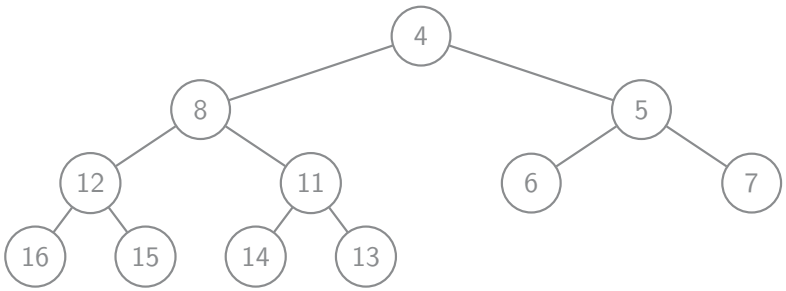

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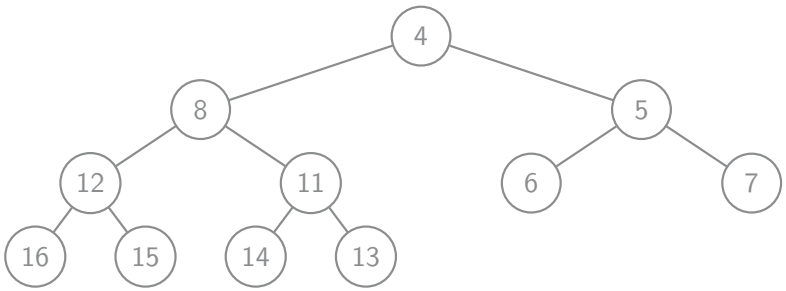
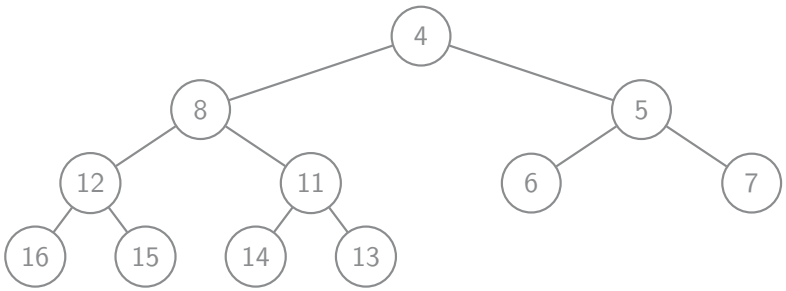
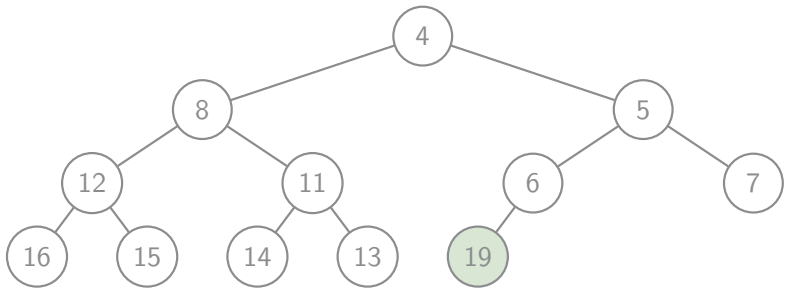



add 19

# Binary Min-Heap



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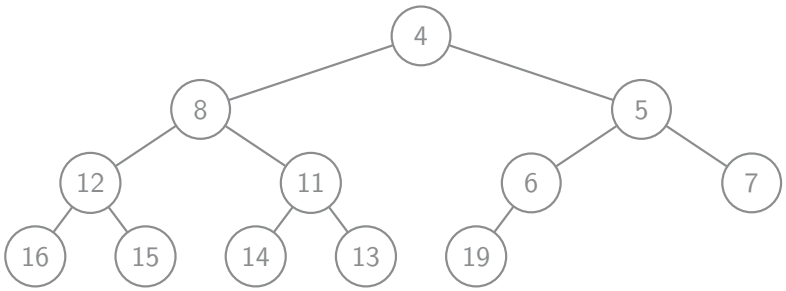

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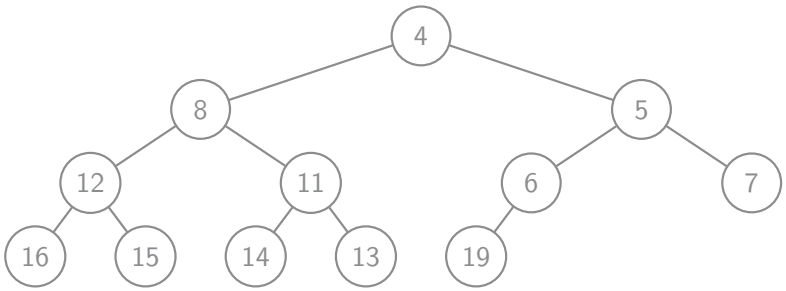

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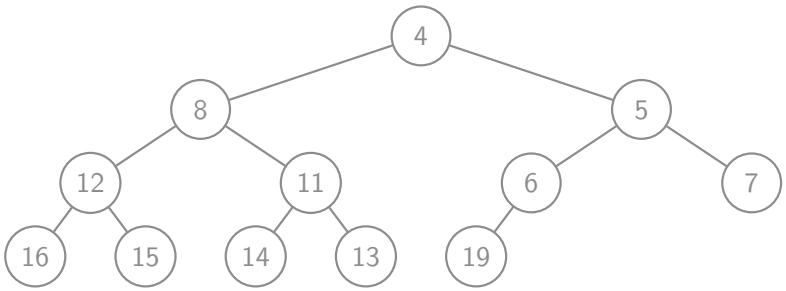


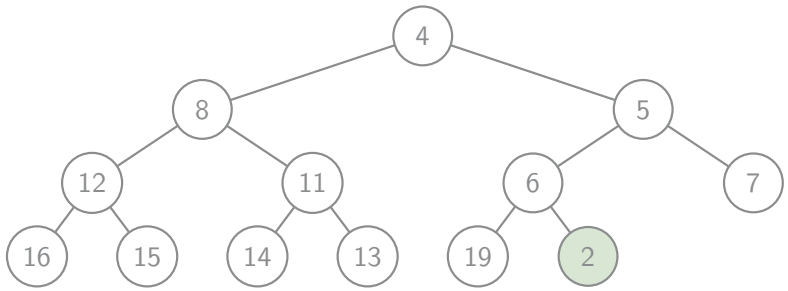

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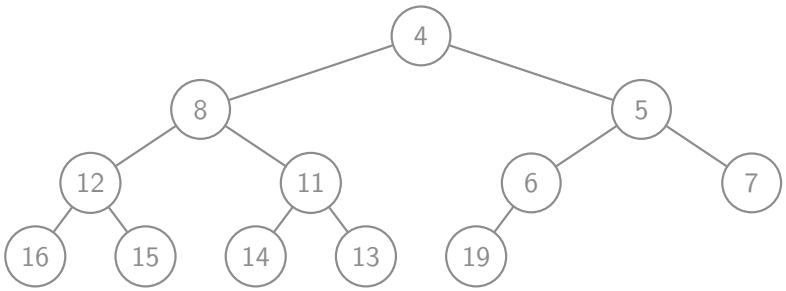


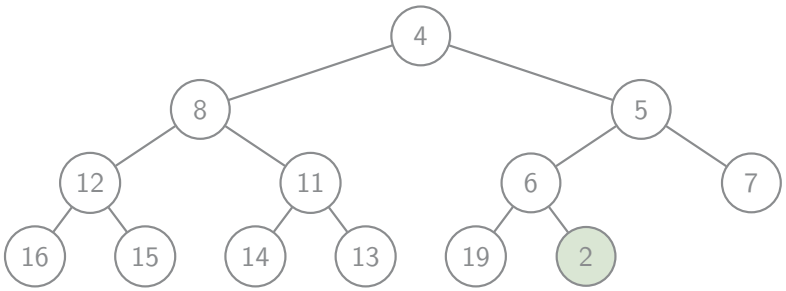


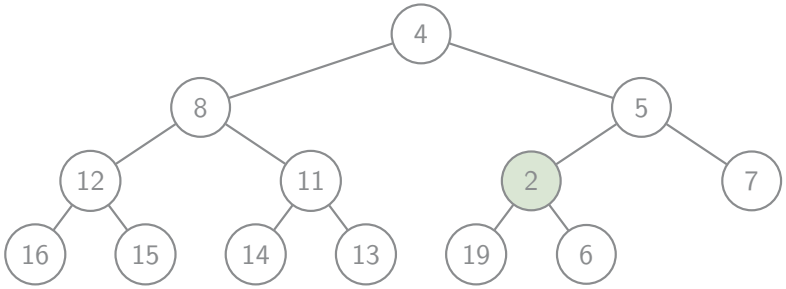

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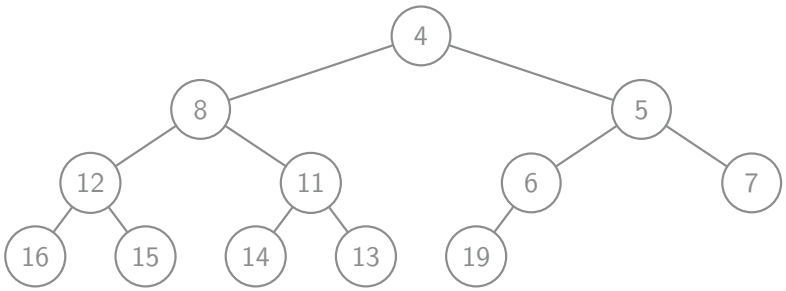


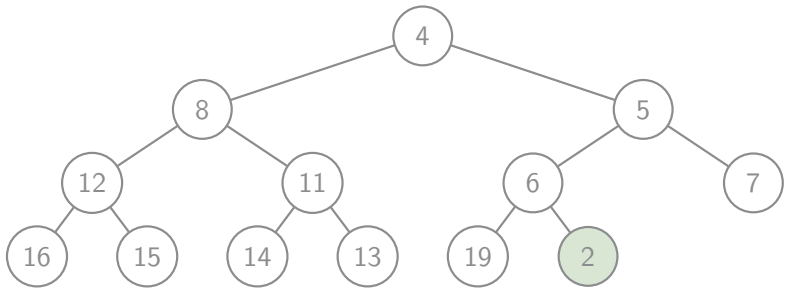


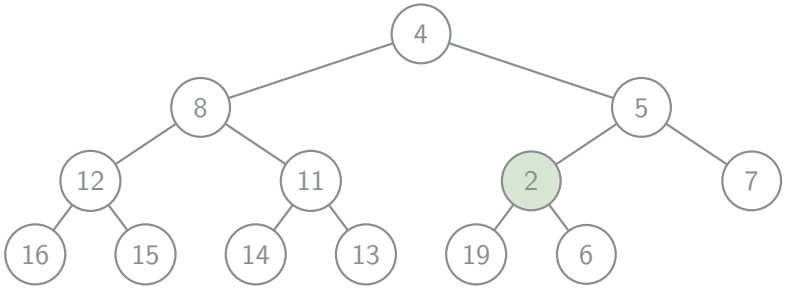


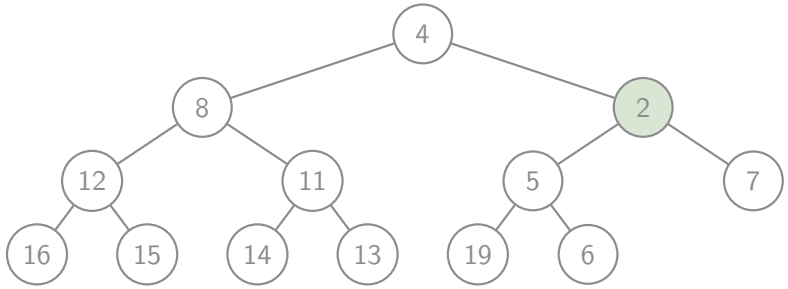

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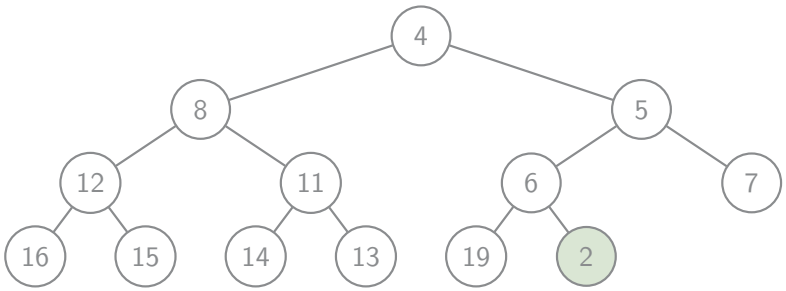


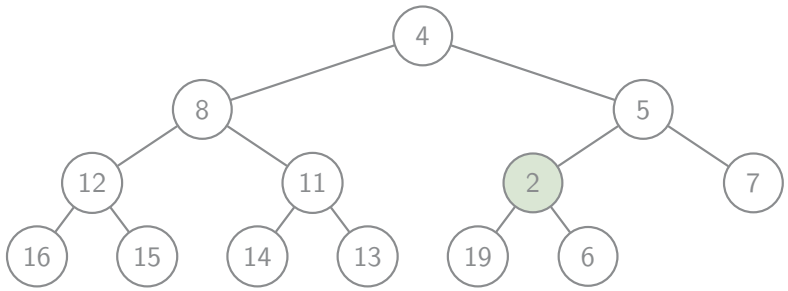


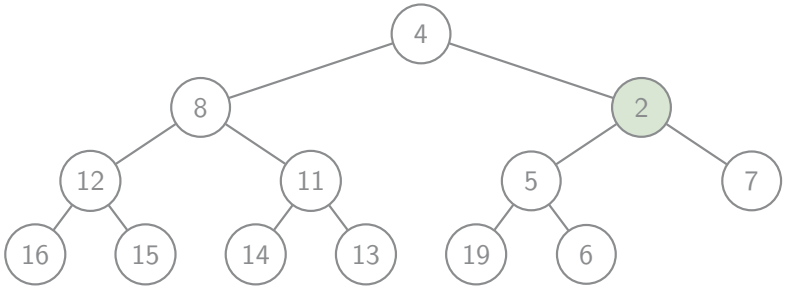

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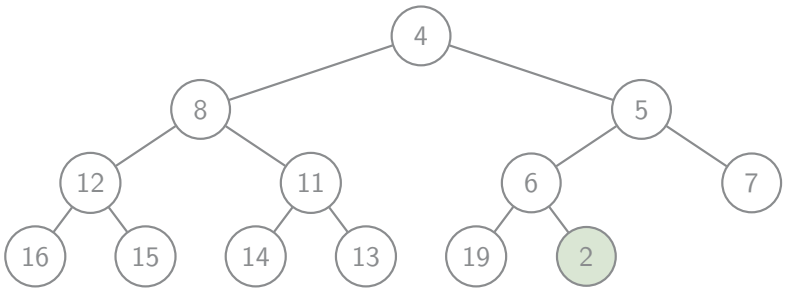


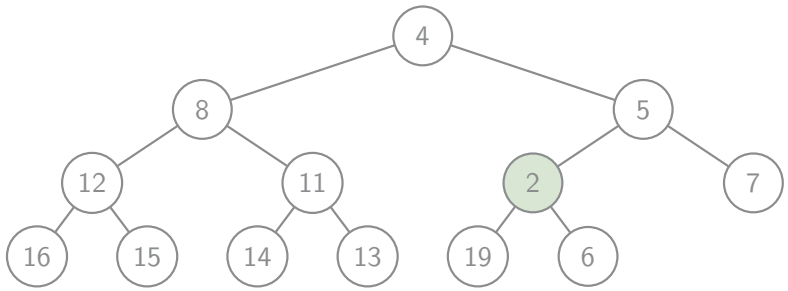


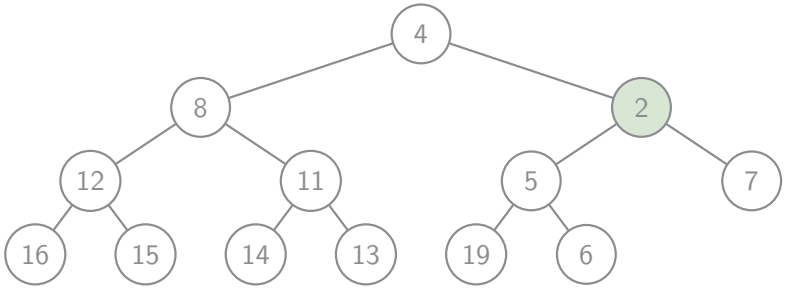


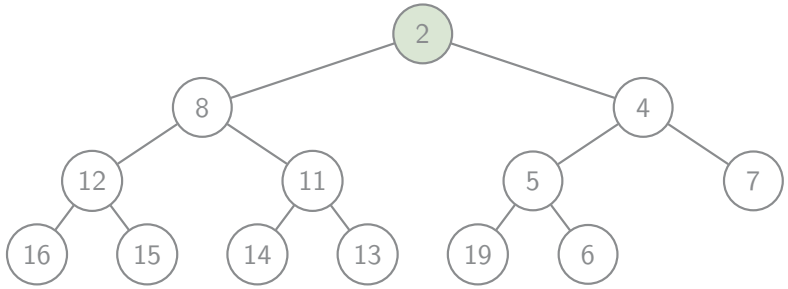

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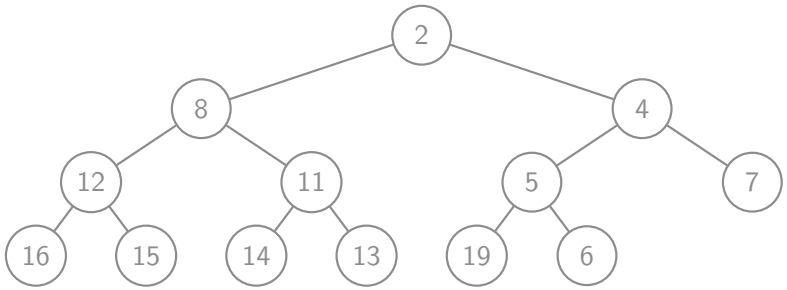

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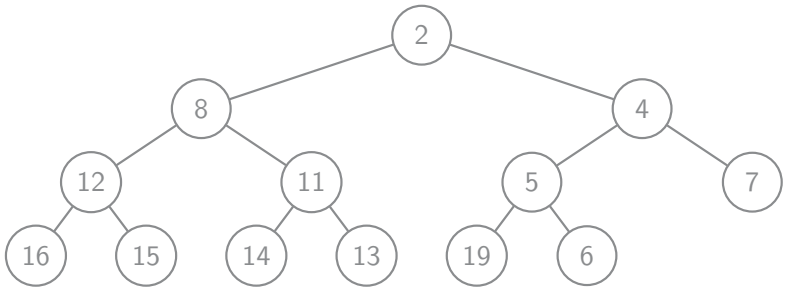
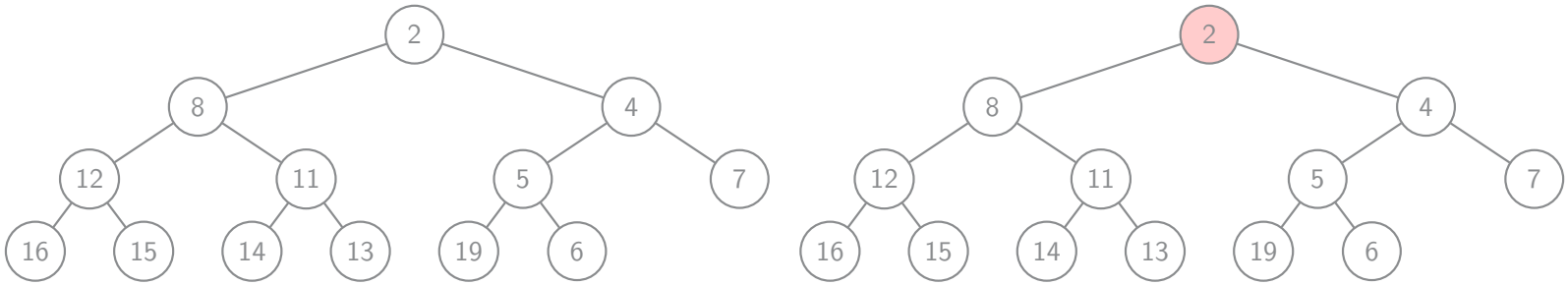



`poll`

# Binary Min-Heap



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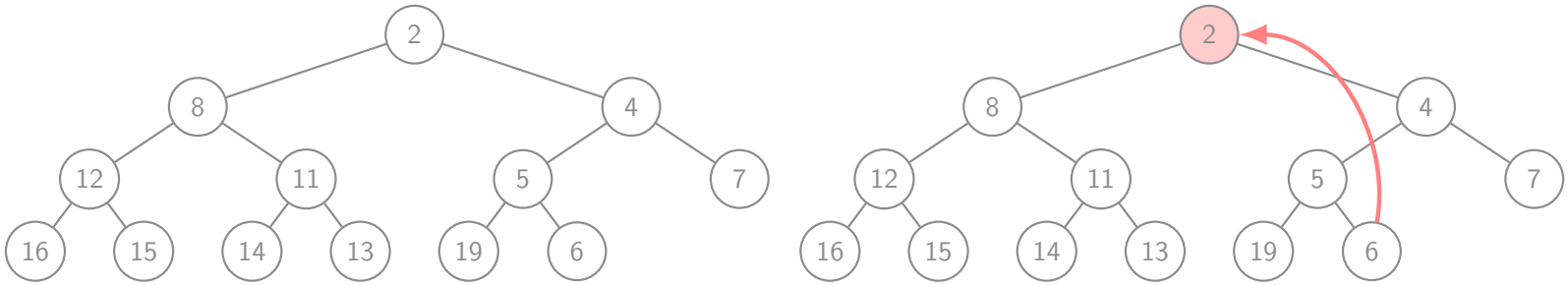

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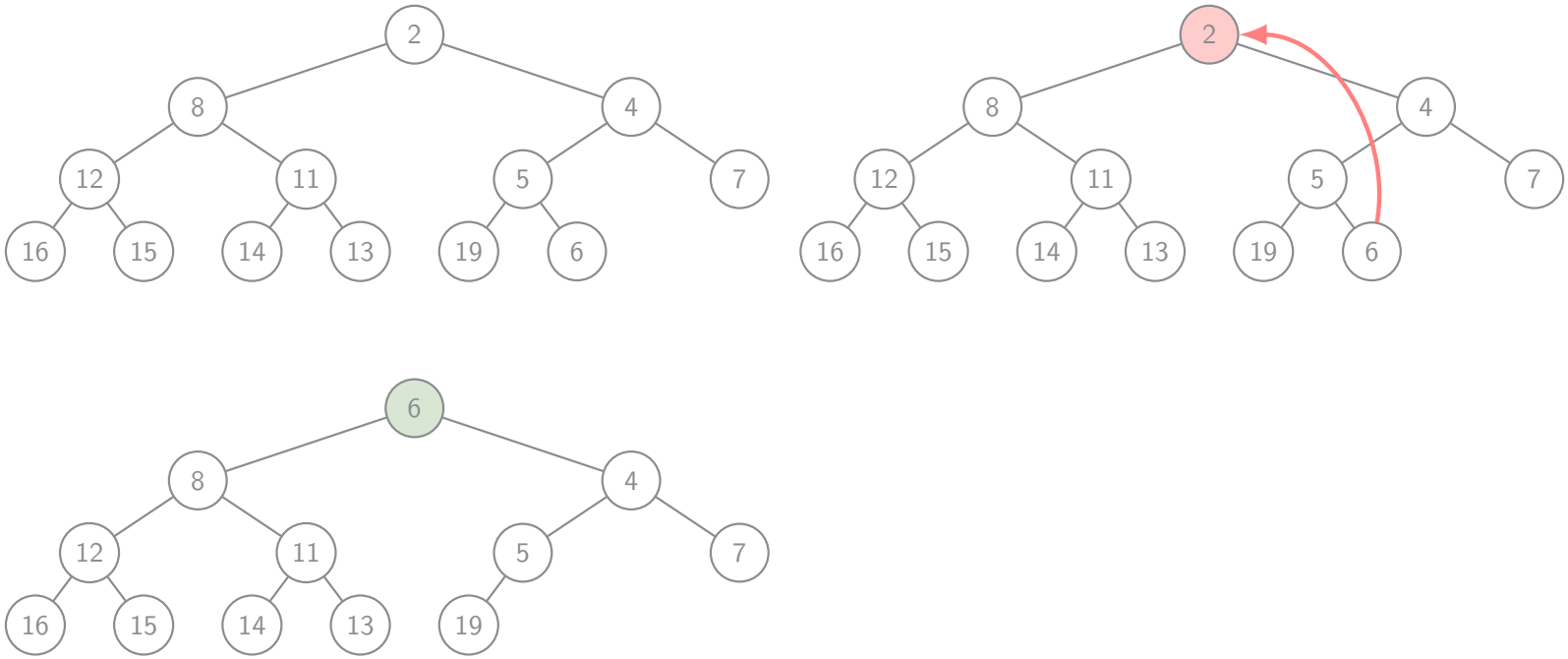

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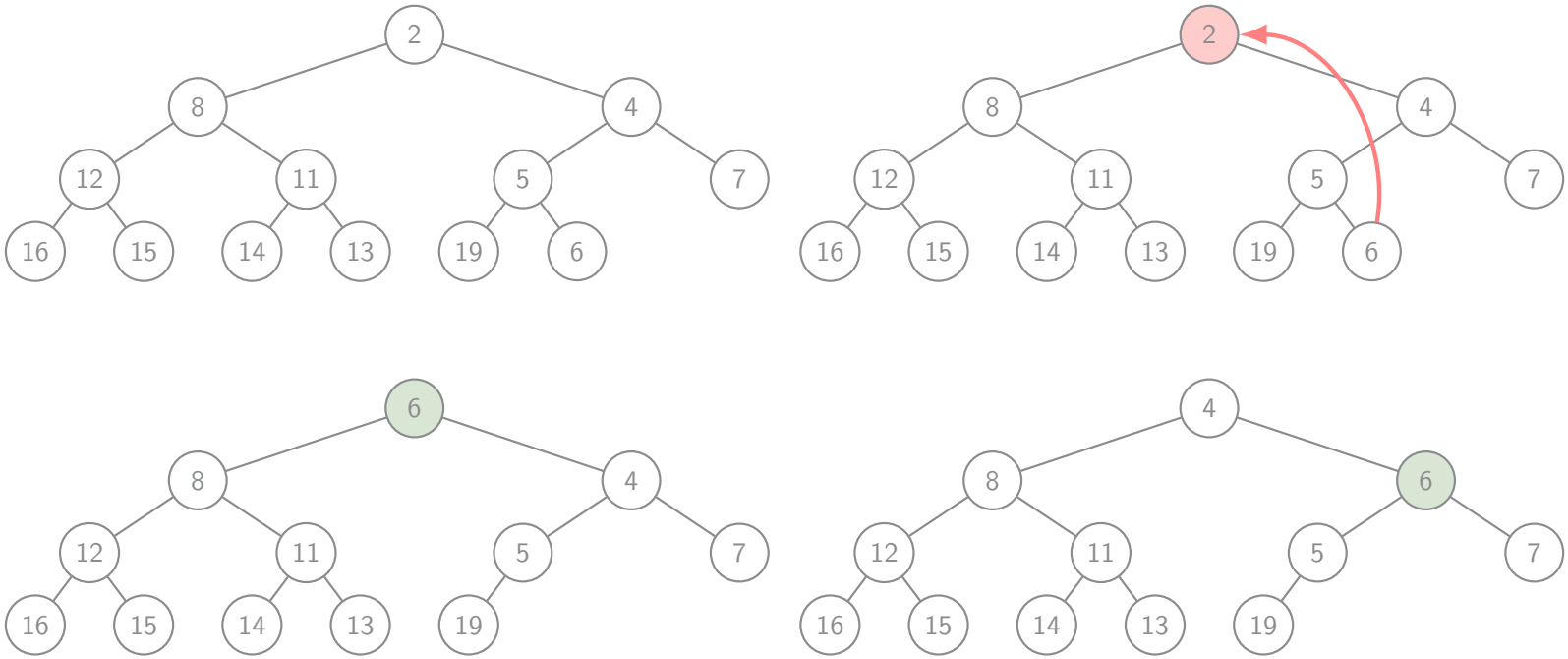

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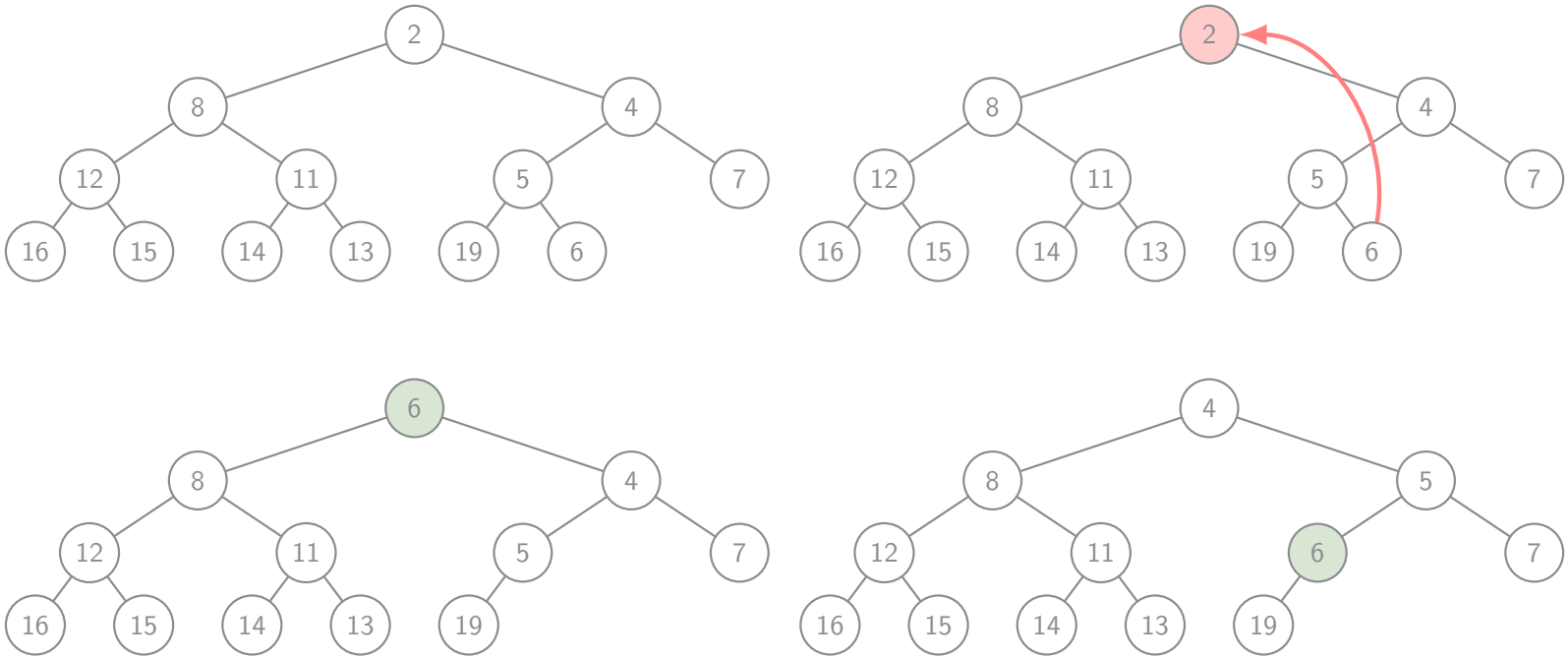


# Binary Min-Heap

## Operations

- `insert`
- `removeAt`
- `peek`
- `poll`

# Binary Min-Heap

## Operations

- `insert` $O(\log n)$
- `removeAt` $O(\log n)$
- `peek` $O(1)$
- `poll` $O(\log n)$

# Binary Min-Heap

## Operations

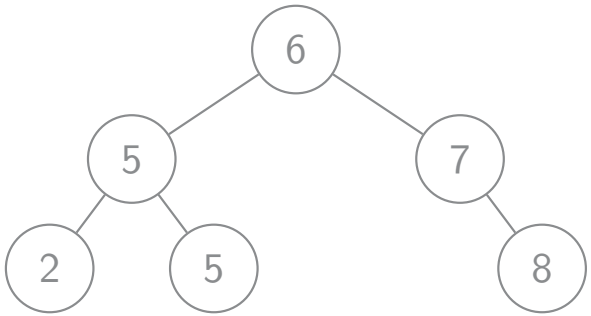
- `insert` $O(\log n)$
- `removeAt` $O(\log n)$
- `peek` $O(1)$
- `poll` $O(\log n)$

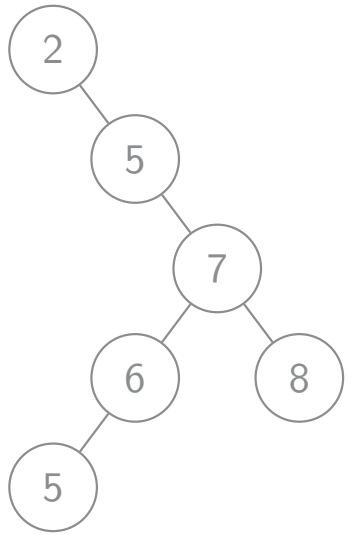
- Heapsort
- Frequently used in Priority Queues

# Binary Search Tree

## Definition

A binary tree in which the left child $\leq$ the parent and the right child $\geq$ the parent.



# Binary Search Tree

## Operations

- `insert` $O(\log n)$ / $O(n)$
- `delete` $O(\log n)$ / $O(n)$
- `search` $O(\log n)$ / $O(n)$

# Red-Black Tree

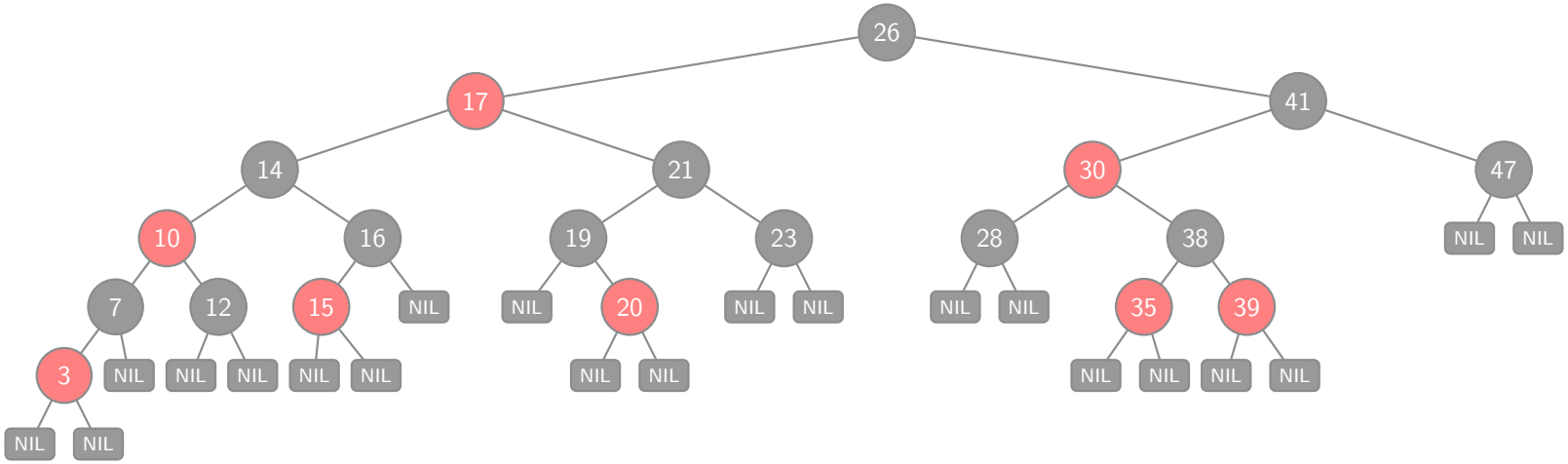
- Binary search tree
- Approximately balanced
- NIL leaves
- Red-black properties

# Red-Black Tree

- Binary search tree
- Approximately balanced
- NIL leaves
- Red-black properties
  - Every node is either red or black
  - Root is black
  - Every leaf is black
  - If a node is red, its children are black
  - For each node, all paths to its descendant leaves contain the same number of black nodes

# Red-Black Tree

- Node is either red or black
- Every leaf is black
- Root is black
- If red, children are black
- $\forall$ node: all paths to its leaves have the same number of black nodes



# Outline

1 Introductory Data Structures
- Array
- Linked List
- Hash Table
- Tree

2 Java Collection API & Map API
- Java Collection API
- Java Map API

3 Advanced Data Structures
- Bloom Filter
- Rope
- Skiplist
- Merkle Tree
- Union Find
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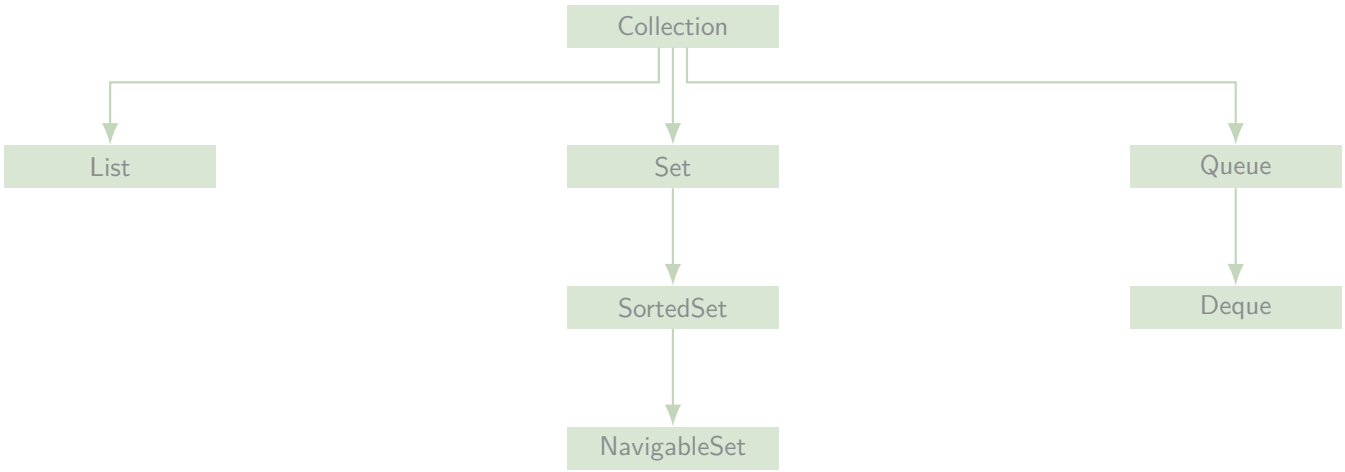
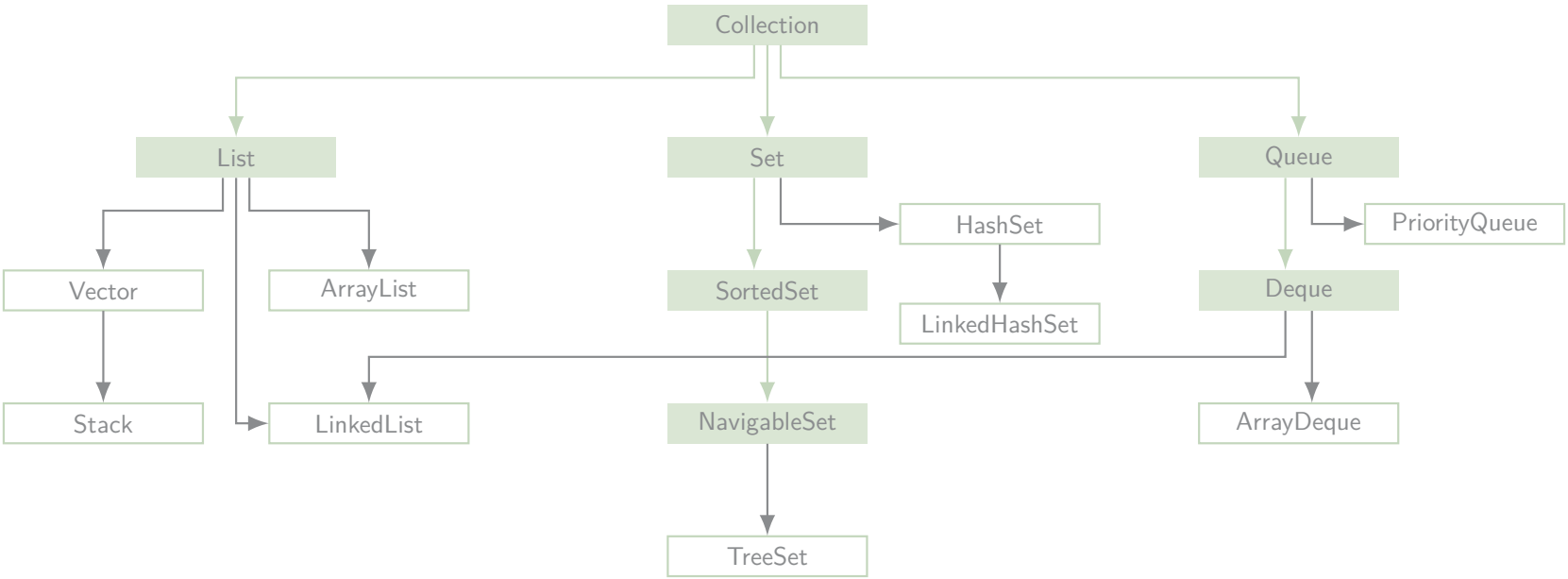
# Java Collection API



# Java Collection API



# List Interface

| | Impl | `add` | `remove` | `contains` | `get` |
|---|---|---|---|---|---|
| LinkedList | linked list | | | | |
| ArrayList | array | | | | |
| Vector | array | | | | |
| Stack | array | | | | |

# List Interface

| | Impl | `add` | `remove` | `contains` | `get` |
|---|---|---|---|---|---|
| LinkedList | linked list | $O(1)$ | | | |
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# List Interface

| | Impl | `add` | `remove` | `contains` | `get` |
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| LinkedList | linked list | $O(1)$ | $O(1)$ | $O(n)$ | $O(n)$ |
| ArrayList | array | $O(1)$ | $O(n)$ | $O(n)$ | $O(1)$ |
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| Stack | array | | | | |

# List Interface

| | Impl | `add` | `remove` | `contains` | `get` |
|---|---|---|---|---|---|
| LinkedList | linked list | $O(1)$ | $O(1)$ | $O(n)$ | $O(n)$ |
| ArrayList | array | $O(1)$ | $O(n)$ | $O(n)$ | $O(1)$ |
| Vector | array | $O(1)$ | $O(n)$ | $O(n)$ | $O(1)$ |
| Stack | array | $O(1)$ | $O(n)$ | $O(n)$ | $O(1)$ |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | | | |
| LinkedHashSet | hash table<br>linked list | | | |
| TreeSet | red-black tree | | | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | | |
| LinkedHashSet | hash table<br>linked list | | | |
| TreeSet | red-black tree | | | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | $O(1)$ | |
| LinkedHashSet | hash table<br>linked list | | | |
| TreeSet | red-black tree | | | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | $O(1)$ | $O(h/n)$ |
| LinkedHashSet | hash table<br>linked list | | | |
| TreeSet | red-black tree | | | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | $O(1)$ | $O(h/n)$ |
| LinkedHashSet | hash table<br>linked list | $O(1)$ | | |
| TreeSet | red-black tree | | | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | $O(1)$ | $O(h/n)$ |
| LinkedHashSet | hash table<br>linked list | $O(1)$ | $O(1)$ | |
| TreeSet | red-black tree | | | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | $O(1)$ | $O(h/n)$ |
| LinkedHashSet | hash table<br>linked list | $O(1)$ | $O(1)$ | $O(1)$ |
| TreeSet | red-black tree | | | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | $O(1)$ | $O(h/n)$ |
| LinkedHashSet | hash table<br>linked list | $O(1)$ | $O(1)$ | $O(1)$ |
| TreeSet | red-black tree | $O(\log n)$ | | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | $O(1)$ | $O(h/n)$ |
| LinkedHashSet | hash table<br>linked list | $O(1)$ | $O(1)$ | $O(1)$ |
| TreeSet | red-black tree | $O(\log n)$ | $O(\log n)$ | |

# Set Interface

| | Impl | `add` | `contains` | `next` |
|---|---|---|---|---|
| HashSet | hash table | $O(1)$ | $O(1)$ | $O(h/n)$ |
| LinkedHashSet | hash table<br>linked list | $O(1)$ | $O(1)$ | $O(1)$ |
| TreeSet | red-black tree | $O(\log n)$ | $O(\log n)$ | $O(\log n)$ |

# Queue Interface

| | Impl | `offer` | `peak` | `poll` |
|---|---|---|---|---|
| PriorityQueue | binary heap | | | |
| ArrayDeque | array | | | |
| LinkedList | linked list | | | |

# Queue Interface

| | Impl | `offer` | `peak` | `poll` |
|---|---|---|---|---|
| PriorityQueue | binary heap | $O(\log n)$ | | |
| ArrayDeque | array | | | |
| LinkedList | linked list | | | |

# Queue Interface

| | Impl | `offer` | `peak` | `poll` |
|---|---|---|---|---|
| PriorityQueue | binary heap | $O(\log n)$ | $O(1)$ | |
| ArrayDeque | array | | | |
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# Queue Interface

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| PriorityQueue | binary heap | $O(\log n)$ | $O(1)$ | $O(\log n)$ |
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# Queue Interface

| | Impl | `offer` | `peak` | `poll` |
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| PriorityQueue | binary heap | $O(\log n)$ | $O(1)$ | $O(\log n)$ |
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| | Impl | `offer` | `peak` | `poll` |
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| PriorityQueue | binary heap | $O(\log n)$ | $O(1)$ | $O(\log n)$ |
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# Queue Interface

| | Impl | `offer` | `peak` | `poll` |
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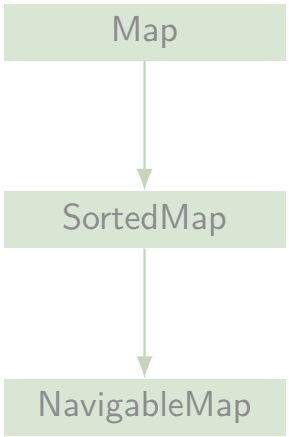
| PriorityQueue | binary heap | $O(\log n)$ | $O(1)$ | $O(\log n)$ |
| ArrayDeque | array | $O(1)$ | $O(1)$ | $O(1)$ |
| LinkedList | linked list | $O(1)$ | $O(1)$ | $O(1)$ |

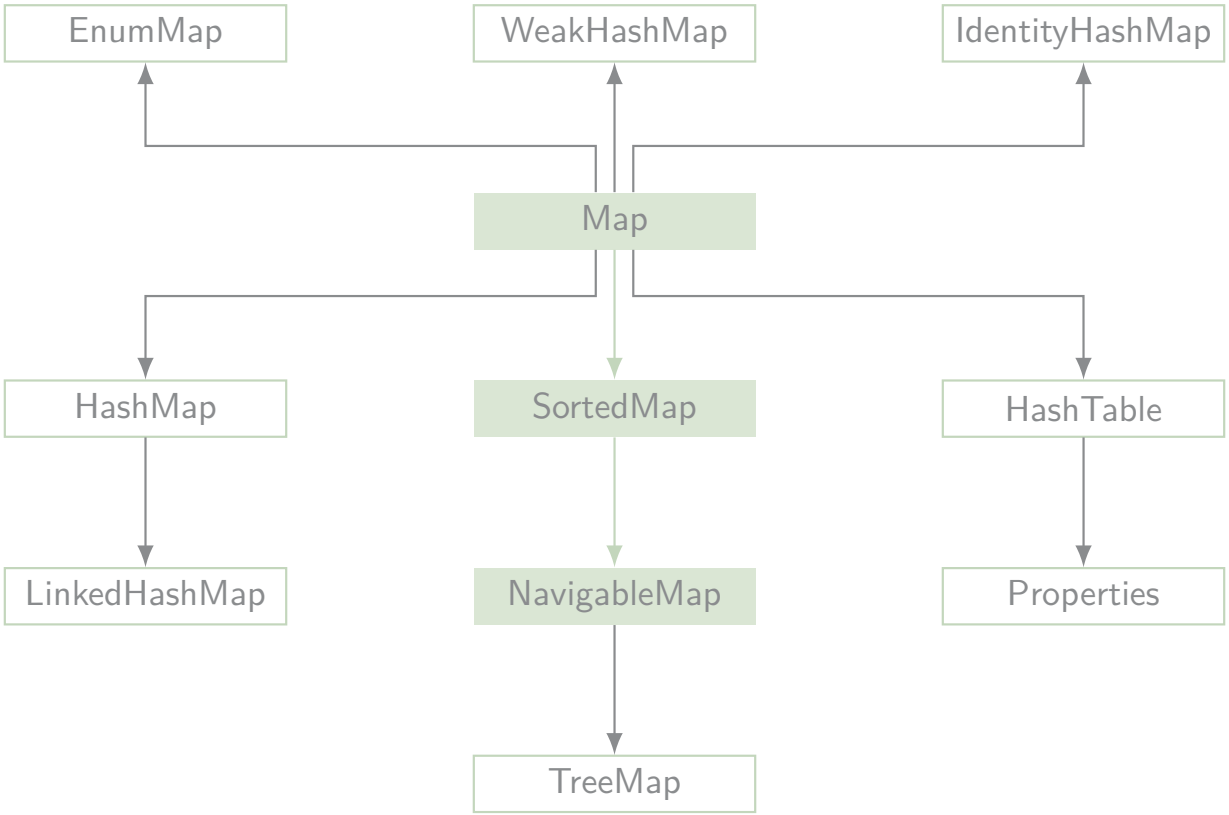
# Outline

1. Introductory Data Structures
   - Array
   - Linked List
   - Hash Table
   - Tree
2. Java Collection API & Map API
   - Java Collection API
   - Java Map API
3. Advanced Data Structures
   - Bloom Filter
   - Rope
   - Skiplist
   - Merkle Tree
   - Union Find
   - Treap

# Java Map API



# Java Map API


EnumMap
WeakHashMap
IdentityHashMap
Map
HashMap
SortedMap
HashTable
LinkedHashMap
NavigableMap
Properties
TreeMap

# Map Interface

| | Impl | `get` | `containsKey` | `next` |
|---|---|---|---|---|
| HashTable | hash table | | | |
| Properties | hash table | | | |
| HashMap | hash table | | | |
| LinkedHashMap | hash table<br>linked list | | | |
| TreeMap | red-black tree | | | |
| IdendityHashMap | array | | | |
| WeekHashMap | hash table | | | |
| EnumMap | array | | | |

# Map Interface

| | Impl | `get` | `containsKey` | `next` |
|---|---|---|---|---|
| HashTable | hash table | $O(1)$ | | |
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| IdendityHashMap | array | $O(1)$ | $O(1)$ | $O(h/n)$ |
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# Bloom Filter

. . .

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# Rope

. . .

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# Skiplist

. . .

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# Merkle Tree

. . .

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# Union Find

. . .

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# Treap

. . .