

# Algorithms and Datastructures

Linked Lists, Binary Search Trees

Prof. Dr. Rolf Backofen

Bioinformatics Group / Department of Computer Science

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# Structure

Sorted Sequences

Linked Lists

Binary Search Trees

# Sorted Sequences

## Introduction

### Structure:

- ▶ We have a set of **keys** mapped to **values**
- ▶ We have a ordering **i** applied to the keys
- ▶ We need the following operations:
  - ▶ **insert(key, value)**: Insert the given pair
  - ▶ **remove(key)**: Remove the pair with the given **key**
  - ▶ **lookup(key)**: Find the element with the given **key**, if it is not available find the element with the next smallest key
  - ▶ **next()/previous()**: Returns the element with the next bigger/smaller **key**. This enables iteration over all elements

# Sorted Sequences

## Introduction

### Application examples:

- ▶ Example: Database for books, products or apartments
- ▶ Large number of records (data sets / tuples)
- ▶ Typical query: Return all apartments with a monthly rent between 400€ and 600€
  - ▶ This is called a **range query**
  - ▶ We can implement this with a combination of **lookup(key)** and **next()**
  - ▶ It's not essential if an apartments exists with **exactly** 400€ monthly rent
- ▶ We do not want to sort all elements every time on an **insert** operation
- ▶ How could we implement this?

# Sorted Sequences

## Implementation 1 (not good) - Static Array

### Static array:

3	5	9	14	18	21	26	40	41	42	43	46
---	---	---	----	----	----	----	----	----	----	----	----

- ▶ **lookup** in time  $O(\log n)$ 
  - ▶ With **binary search**
  - ▶ Example: **lookup(41)**
- ▶ **next** / **previous** in time  $O(1)$ 
  - ▶ They are next to each other
- ▶ **insert** and **remove** up to  $\Theta(n)$ 
  - ▶ We have to copy up to  $n$  elements

# Sorted Sequences

## Implementation 2 (bad) - Hash Table

### Hash map:

- ▶ `insert` and `remove` in  $O(1)$

If the hash table is big enough and we use a good hash function

- ▶ `lookup` in time  $O(1)$

If element with **exactly** this key exists, otherwise we get `None` as result

- ▶ `next` / `previous` in time up to  $\Theta(n)$

Order of the elements is independent of the order of the keys

# Sorted Sequences

## Implementation 3 (good?) - Linked List

### Linked list:

- ▶ Runtimes for doubly linked lists:
  - ▶ `next` / `previous` in time  $O(1)$
  - ▶ `insert` and `remove` in  $O(1)$
  - ▶ `lookup` in time  $\Theta(n)$
- ▶ Not yet what we want, but structure is related to binary search trees
- ▶ Let's have a closer look

# Linked Lists

## Introduction

### Linked list:

- ▶ Dynamic datastructure
- ▶ Number of elements changeable
- ▶ Data elements can be simple types or composed datastructures
- ▶ Elements are linked through references / pointer to the predecessor / successor
- ▶ Single / doubly linked lists possible



Figure: Linked list



# Linked Lists

## Introduction

### **Properties in comparison to an array:**

- ▶ Minimal extra space for storing pointer
- ▶ We do not need to copy elements on `insert` or `remove`
- ▶ The number of elements can be simply modified
- ▶ No direct access of elements  
⇒ We have to iterate over the list

# Linked Lists

## Variants

### List with head / last element pointer:



Figure: Singly linked list

- ▶ Head element has pointer to first list element
- ▶ May also hold additional information:
  - ▶ Number of elements

# Linked Lists

## Variants

### Doubly linked list:



Figure: Doubly linked list

- ▶ Pointer to successor element
- ▶ Pointer to predecessor element
- ▶ Iterate forward and backward

# Linked Lists

## Implementation - Node/Element - Python

```
class Node:
    """ Defines a node of a singly linked
        list.
    """

    def __init__(self, value, nextNode):
        self.value = value
        self.nextNode = nextNode

    def __init__(self, value):
        self.value = value;
        self.nextNode = None
```

# Linked Lists

## Usage examples

### Creating linked lists - Python:

- ▶ `first = Node(7)`



- ▶ `first.nextNode = Node(3)`



- ▶ `first.nextNode.value = 4`



# Linked Lists

## Implementation - Insert

**Inserting a node after node cur:**

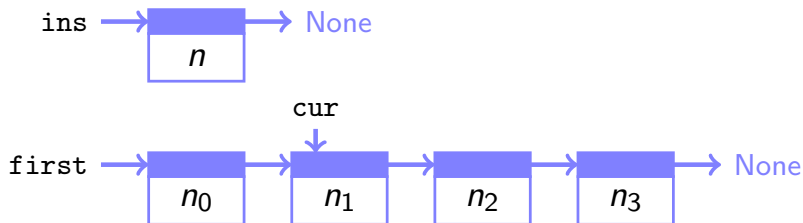


# Linked Lists

## Implementation - Insert

**Inserting a node after node cur:**

► `ins = Node(n)`



# Linked Lists

## Implementation - Insert

**Inserting a node after node cur:**

► `ins.nextNode = cur.nextNode`





# Linked Lists

## Implementation - Insert

**Inserting a node after node `cur`:**

► `cur.nextNode = ins`



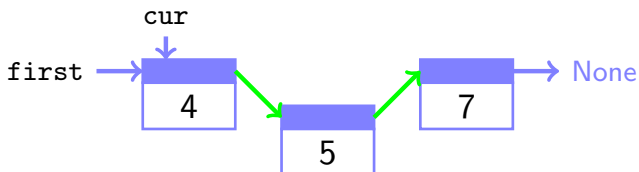
# Linked Lists

## Implementation - Insert

**Inserting a node after node `cur` - single line of code:**



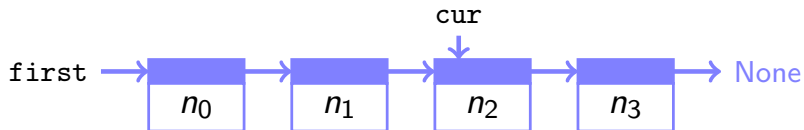
► `cur.nextNode = Node(value, cur.nextNode)`



# Linked Lists

## Implementation - Remove

**Removing a node** `cur`:



# Linked Lists

## Implementation - Remove

### Removing a node `cur`:

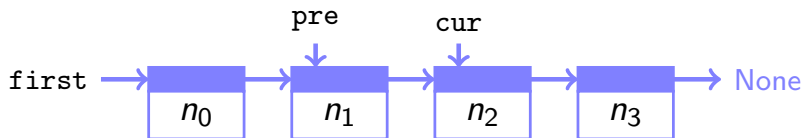
- Find the predecessor of `cur`:

```
pre = first
```

```
while pre.nextNode != cur:
```

```
    pre = pre.nextNode
```

- Runtime of  $O(n)$
- Does not work for first node!



# Linked Lists

## Implementation - Remove

### Removing a node `cur`:

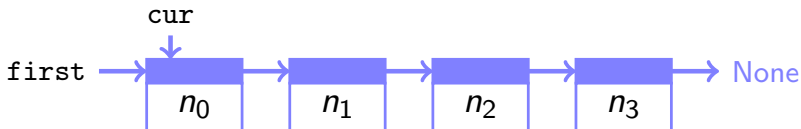
- ▶ Update the pointer to the next element:  
`pre.nextNode = cur.nextNode`
- ▶ `cur` will get automatically destroyed if no more references exist (`cur=None`)



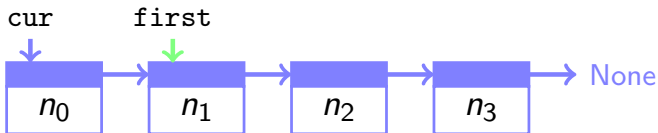
# Linked Lists

## Implementation - Remove

### Removing the first node:



- Update the pointer to the next element:  
`first = first.nextNode`
- `cur` will get automatically destroyed if no more references exist  
(`cur=None`)



# Linked Lists

## Implementation - Remove

**Removing a node** cur: (General case)

```
if cur == first:
    first = first.nextNode
else:
    pre = first
    while pre.nextNode != cur:
        pre = pre.nextNode

    pre.nextNode = cur.nextNode
```

# Linked Lists

## Implementation - Head Node

### Using a head node:

- ▶ Advantage:
  - ▶ Deleting the first node is no special case
- ▶ Disadvantage
  - ▶ We have to consider the first node at other operations
  - ▶ Iterating all nodes
  - ▶ Counting of all nodes
  - ▶ ...





# Linked Lists

## Implementation - LinkedList - Python

```
class LinkedList:
    def __init__(self):
        self.itemCount = 0
        self.head = Node()
        self.last = self.head

    def size(self):
        return self.itemCount

    def isEmpty(self):
        return self.itemCount == 0
```

# Linked Lists

## Implementation - LinkedList - Python

```
def append(self, value):  
    ...  
  
def insertAfter(self, cur, value):  
    ...  
  
def remove(self, cur):  
    ...  
  
def get(self, position):  
    ...  
  
def contains(self, value):  
    ...
```

# Linked Lists

## Implementation

### Head, last:

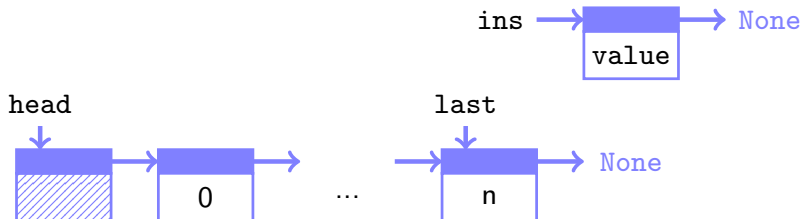


- ▶ Head points to the first node, last to the last node
- ▶ We can append elements to the end of the list in  $O(1)$  through the last node
- ▶ We have to keep the pointer to last updated after all operations

# Linked Lists

## Implementation - Append

### Appending an element:



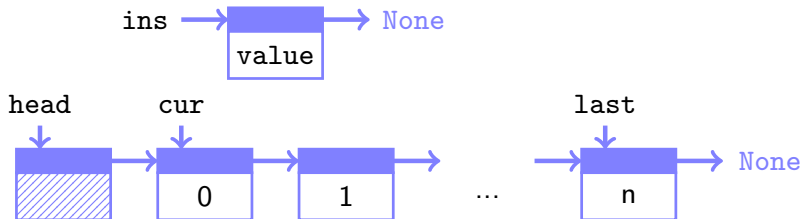
```
def append(self, value):  
    last.nextNode = Node(value)  
    last = last.NextNode  
    itemCount += 1
```

- The pointer to last avoids the iteration of the whole list

# Linked Lists

## Implementation - Insert After

**Inserting after node cur:**



# Linked Lists

## Implementation - Insert After

### Inserting after node cur:

- The pointer to head is not modified

```
def insertAfter(self, cur, value):  
    if cur == last:  
        # also update last node  
        append(value)  
    else:  
        # last node is not modified  
        cur.nextNode = Node(value, \  
                             cur.nextNode)  
        itemCount += 1
```

# Linked Lists

## Implementation - Remove

**Remove node** `cur`:



# Linked Lists

## Implementation - Remove

### Remove node cur:

- ▶ Searching the predecessor in  $O(n)$

```
def remove(self, cur):  
    pre = first  
    while pre.nextNode != cur:  
        pre = pre.nextNode  
  
    pre.nextNode = cur.nextNode  
    itemCount -= 1  
  
    if pre.nextNode == None:  
        last = pre
```



# Linked Lists

## Implementation - Get

### Getting a reference to node at pos:

- Iterate the entries of the list until at position in  $O(n)$

```
def get(self, pos):  
    if pos < 0 or pos >= itemCount:  
        return None  
  
    cur = head  
    for i in range(0, pos):  
        cur = cur.nextNode  
  
    return cur
```

# Linked Lists

## Implementation - Contains

### Searching a value:

- ▶ First element is head without an assigned value
- ▶ Iterate the entries of the list until value found in  $O(n)$

```
def contains(self, value):  
    cur = head  
  
    for i in range(0, itemCount):  
        cur = cur.nextNode  
        if cur.value == value:  
            return True  
  
    return False
```

# Linked Lists

## Runtime

### Runtime:

- ▶ Singly linked list:
  - ▶ `next` in  $O(1)$
  - ▶ `previous` in  $\Theta(n)$
  - ▶ `insert` in  $O(1)$
  - ▶ `remove` in  $\Theta(n)$
  - ▶ `lookup` in  $\Theta(n)$
- ▶ Better with doubly linked lists

# Linked Lists

## Doubly Linked List

### Doubly linked list:

- ▶ Each node has a reference to its successor and its predecessor
- ▶ We can iterate the list forward and backward

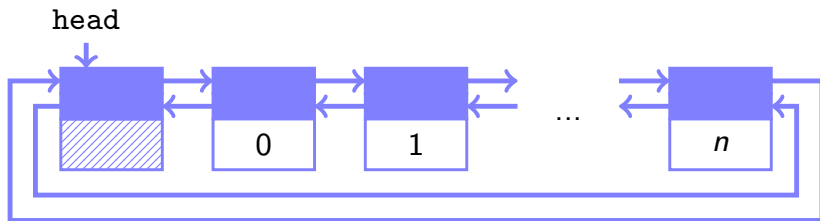


# Linked Lists

## Doubly Linked List

### Doubly linked list:

- ▶ It is helpful to have a **head** node
- ▶ We only need **one head** node if we connect the list cyclic



# Linked Lists

## Runtime

### Runtime of doubly linked list:

- ▶ `next` and `previous` in  $O(1)$

Each element has a pointer to pred-/sucessor

- ▶ `insert` and `remove` in  $O(1)$

A constant number of pointers needs to be modified

- ▶ `lookup` in  $\Theta(n)$

Even if the elements are sorted we can only retrieve them in  $\Theta(n)$  Why?

# Linked Lists

List in real program

**Linked list in book:**



# Linked Lists

List in real program

## Linked list in memory:





# Binary Search Trees

## Introduction

### Runtime of a search tree:

- ▶ `next` and `previous` in  $O(1)$

Pointers corresponding to linked list

- ▶ `insert` and `remove` in  $O(\log n)$

- ▶ `lookup` in  $O(\log n)$

The structure helps searching efficiently

# Binary Search Trees

## Introduction

### Idea:

- ▶ We define a total order for the search tree
- ▶ All nodes of the left subtree have **smaller keys** than the current node
- ▶ All nodes of the right subtree have **bigger keys** than the current node

# Binary Search Trees

## Introduction

- Edge direction indicates ordering

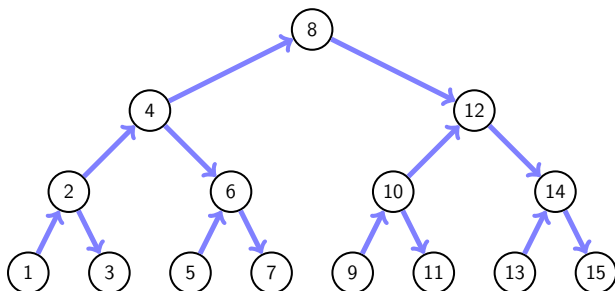


Figure: A binary search tree

# Binary Search Trees

## Introduction

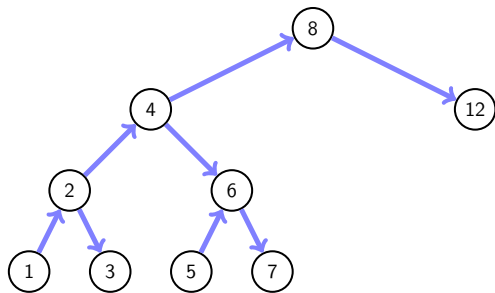


Figure: Another binary search tree

# Binary Search Trees

## Introduction

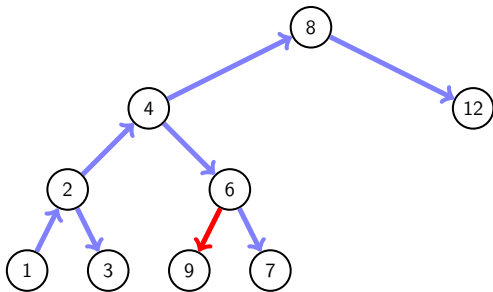


Figure: **Not** a binary search tree

# Binary Search Trees

## Implementation

### Implementation:

- ▶ For the heap we had all elements stored in an array
- ▶ Here we link all nodes through pointer / references, like linked lists
- ▶ Each node has a pointer / reference to its children (`leftChild` / `rightChild`)
- ▶ `None` for missing children



# Binary Search Trees

## Implementation

### Implementation:

- ▶ We create a sorted doubly linked list of all elements
- ▶ This enables an efficient implementation of (`next` / `previous`)



Figure: Binary search tree with links

# Binary Search Trees

## Implementation - Lookup

### Lookup:

- ▶ Definition:  
“ Search the element with the given key. If no element is found return the element with the next (bigger) key. ”
- ▶ We search from the root downwards:
  - ▶ Compare the searched key with the key of the node
  - ▶ Go to the left / right until the child is **None** or the key is found
  - ▶ If the key is not found return the next bigger one



# Binary Search Trees

## Implementation - Lookup

**For each node applies the total order:**

keys of left subtree | `node.key` | keys of right subtree



**Examples:**

`lookup(14)`

`lookup(6)`

`lookup(19)`

Figure: Binary search tree with total order “`i`”

# Binary Search Trees

## Implementation - Insert

### Insert:

- ▶ We search for the key in our search tree
- ▶ If a node is found we replace the value with the new one
- ▶ Else we insert a new node
- ▶ If the key was not present we get a **None** entry
- ▶ We insert the node there

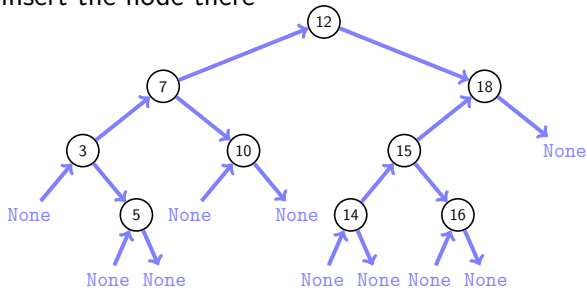


Figure: Binary search tree with total order “i”

# Binary Search Trees

## Implementation - Remove

**Remove:** Case 1: The node "5" has no children

- ▶ Find **parent** of node "5" ("6")
- ▶ Set left / right child of node "6" to **None** depending on position of node "5"

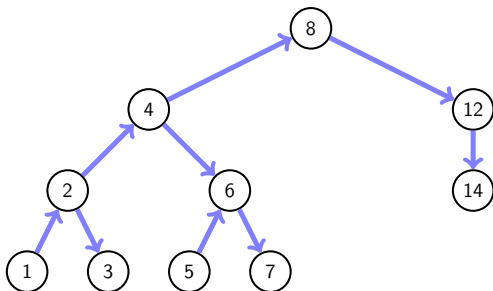


Figure: Binary search tree with total order "i"

# Binary Search Trees

## Implementation - Remove

**Remove:** Case 1: The node "5" has no children

- ▶ Find **parent** of node "5" ("6")
- ▶ Set left / right child of node "6" to **None** depending on position of node "5"



Figure: Binary search tree after deleting node "5"

# Binary Search Trees

## Implementation - Remove

**Remove:** Case 2: The node "12" has one child

- ▶ Find the **child** of node "12" ("14")
- ▶ Find the **parent** of node "12" ("8")
- ▶ Set left / right **child** of node "8" to "14" depending on position of node "12" (skip node "14")



Figure: Binary search tree with total order "i"

# Binary Search Trees

## Implementation - Remove

**Remove:** Case 2: The node "12" has one child

- ▶ Find the **child** of node "12" ("14")
- ▶ Find the **parent** of node "12" ("8")
- ▶ Set left / right **child** of node "8" to "14" depending on position of node "12" (skip node "14")

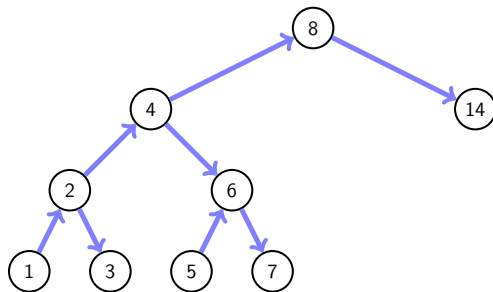


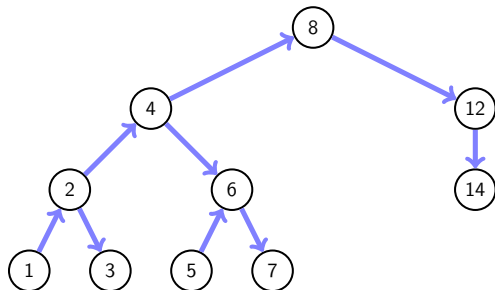
Figure: Binary search tree after deleting node "12"

# Binary Search Trees

## Implementation - Remove

**Remove:** Case 3: The node “4” has two children

- ▶ Find the **successor** of node “4” (“5”)
- ▶ Replace the value of node “4” with the value of node “5”
- ▶ Delete node “5” (the **successor** of node “4”) with remove-case 1 or 2
- ▶ There is no left node because we are deleting the **predecessor**



# Binary Search Trees

## Implementation - Remove

**Remove:** Case 3: The node “4” has two children

- ▶ Find the **successor** of node “4” (“5”)
- ▶ Replace the value of node “4” with the value of node “5”
- ▶ Delete node “5” (the **successor** of node “4”) with remove-case 1 or 2
- ▶ There is no left node because we are deleting the **predecessor**





# Binary Search Trees

## Runtime Complexity

### How long takes *insert* and *lookup*?

- ▶ Up to  $\Theta(d)$ , with  $d$  being the *depth of the tree* (The longest path from the root to a leaf)
- ▶ *Best case* with  $d = \log n$  the runtime is  $\Theta(\log n)$
- ▶ *Worst case* with  $d = n$  the runtime is  $\Theta(n)$
- ▶ If we **always** want to have a runtime of  $\Theta(\log n)$  then we have to *rebalance* the tree

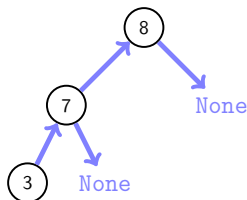


Figure: Degenerated binary tree  $d = n$

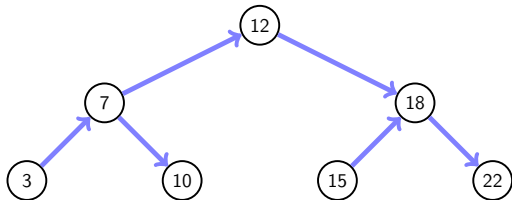


Figure: Complete binary tree  $d = \log n$

► **General**

[CRL01] Thomas H. Cormen, Ronald L. Rivest, and Charles E. Leiserson.

*Introduction to Algorithms.*

MIT Press, Cambridge, Mass, 2001.

[MS08] Kurt Mehlhorn and Peter Sanders.

Algorithms and data structures, 2008.

<https://people.mpi-inf.mpg.de/~mehlhorn/ftp/Mehlhorn-Sanders-Toolbox.pdf>.

## ► **Linked List**

[Wik] [Linked list](https://en.wikipedia.org/wiki/Linked_list)

`https://en.wikipedia.org/wiki/Linked\_list`

## ► **Binary Search Tree**

[Wik] [Binary search tree](https://en.wikipedia.org/wiki/Binary_search_tree)

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