

Algorithms and Datastructures

Linked Lists, Binary Search Trees

Albert-Ludwigs-Universität Freiburg



**UNI
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Bioinformatics Group / Department of Computer Science
Algorithms and Datastructures, January 2017

Feedback

Exercises

Lecture

Sorted Sequences

Linked Lists

Binary Search Trees

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Feedback from the exercises



- The few people who gave feedback wrote that it was simple to doable.

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- Missing support in forum

Feedback from the lecture

- Added german lecture recordings to current semester page

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- Lecture recordings are now password protected

Feedback

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Structure:

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 - **lookup(key)**: Find the element with the given **key**, if it is not available find the element with the smallest key $>$ **key**
 - **next()/previous()**: Returns the element with the next bigger/smaller **key**. This enables iteration over all elements.



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- We do not want to sort all elements every time on an **insert** operation
- How could we implement this?

Static array:

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---	---	---	----	----	----	----	----	----	----	----	----

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 - They are next to each other
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 - We have to copy up to n elements



Hash map:



Hash map:

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- `next` / `previous` in time up to $\Theta(n)$
 - The order of the elements is independent of the order of the keys

Sorted Sequences

Implementation 3 (good?) - Linked List



Linked list:

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- Runtimes for doubly linked lists:

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Linked list:

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

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Binary Search Trees



Linked list:



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- Dynamic datastructure



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- Single / Doubly linked lists possible

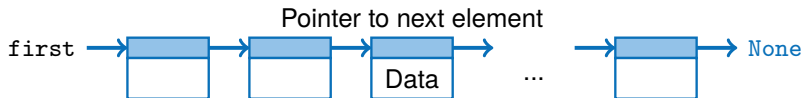


Figure: Linked list



Properties in comparison to an array:



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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



List with head / last element pointer:

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Figure: Singly linked list

List with head / last element pointer:

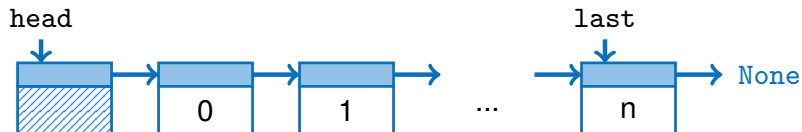


Figure: Singly linked list

- Head element has pointer to first list element

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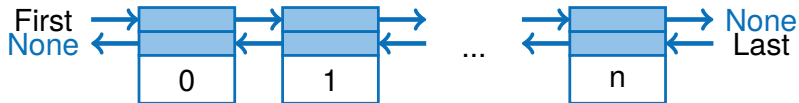


Figure: Doubly linked list

- Pointer to successor element

Doubly linked list:

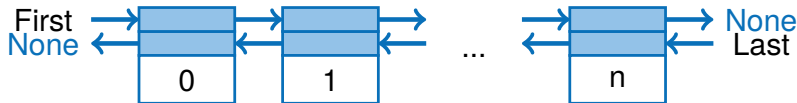


Figure: Doubly linked list

- Pointer to successor element
- Pointer to predecessor element

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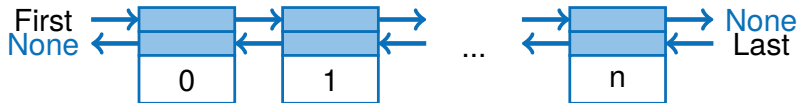


Figure: Doubly linked list

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



```
public class Listelem
```



```
public class Listelem  
{    //2 fields: integer and reference
```



```
public class Listelem
{
    //2 fields: integer and reference
    //private only available in class
    private int data;
    private Listelem next;
```



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    //2 constructors: for instance of class
    public Listelem(int d)
    { data = d; next = null; }
```

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    //adopted from Mary K.Vernon
    //Introduction to Data Structures
```

Linked Lists

Implementation - Node/Element - Java



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```
//Function to read and write private fields  
public int getData() {return data; }  
public void setData(int d) { data = d; }
```



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//Function to read and write private fields  
public int getData() {return data; }  
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public int getData() {return data; }
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//Integer represents possible data, e.g.
//self defined reference datatypes
}
```

Linked Lists

Implementation - Node/Element - C++



```
class Listelem  
{
```



```
class Listelem
{
private:
    int data;
    Listelem* next;
```

```
class Listelem
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Linked Lists

Implementation - Node/Element - C++



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int getData() { return data; }  
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```
Listelem* getNext() { return next; }  
void setNext(Listelem* n) { next = n; }  
}
```

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

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

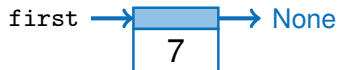
    def __init__(self, value):
        self.value = value;
        self.nextNode = None
```



Creating linked lists - Python:

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```
■ first = Node(7)
```



Creating linked lists - Python:

■ `first = Node(7)`



■ `first.nextNode = Node(3)`



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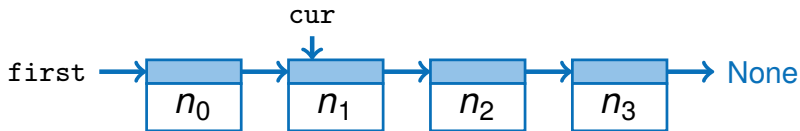
■ `first.nextNode = Node(3)`



■ `first.nextNode.value = 4`



Inserting a node after node `cur`:





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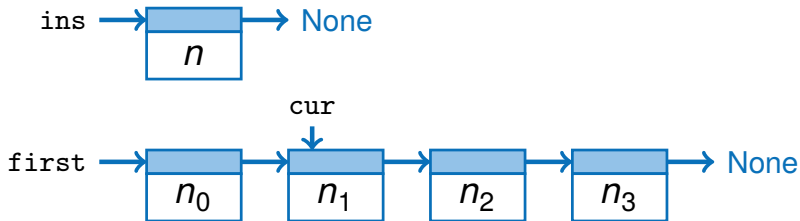


Inserting a node after node `cur`:

- `ins = Node(n)`

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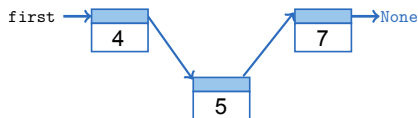


■ `cur.nextNode = Node (value ,cur.nextNode)`

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



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Removing a node `cur`:





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Removing a node `cur`:

- Find the predecessor of `cur`:

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while pre.nextNode != cur:
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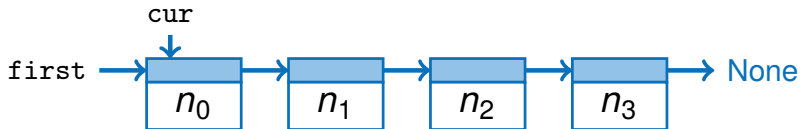
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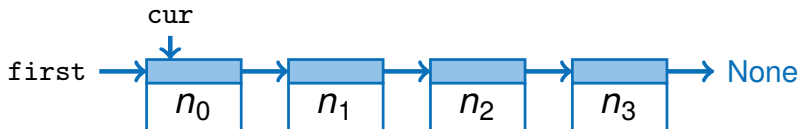


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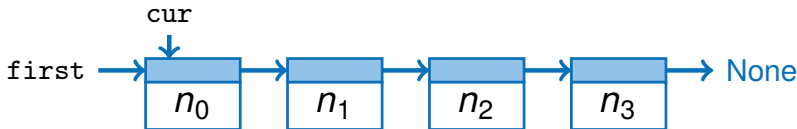
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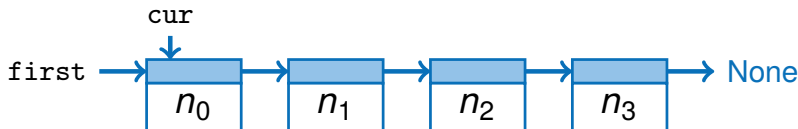
```
first = first.nextNode
```

Removing the first node:

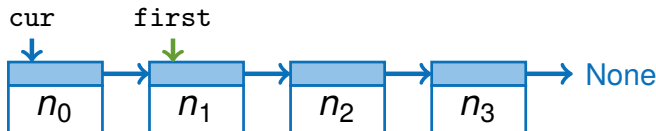


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Removing the first node:



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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
```



Using a head node:



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 - Deleting the first node is no special case
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 - ...



```
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
```

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

```
/**
 * A singly linked list with data type int.
 */
public class LinkedList {

    private long itemCount;
    private Node head;
    private Node last;

    public LinkedList() {
        itemCount = 0;
        head = new Node();
        last = head;
    }
}
```

```
    public int size() {
        return itemCount;
    }

    public boolean isEmpty() {
        return (itemCount == 0);
    }

    public void add (int data) { ... }
    public void insertAfter(Node cur, int data)
        { ... }
    public void remove(Node cur) { ... }
    public Node get(int position) { ... }
    public boolean contains( int data) { ... }
}
```

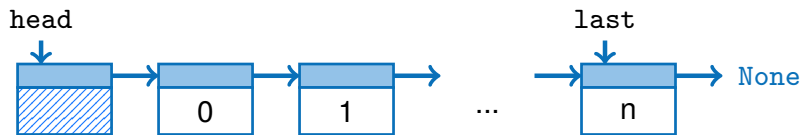


Head, last:

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- Head points to the first node, last to the last node

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- We can append elements to the end of the list in $O(1)$ through the last node

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

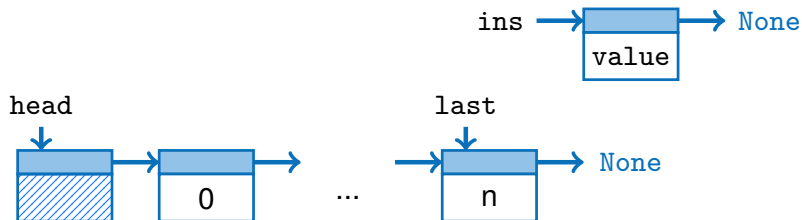


Appending an element:

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Appending an element:



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

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



### Inserting after node `cur`:





**Inserting after node `cur`:**



### Inserting after node `cur`:

- The pointer to `head` is not modified

### 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
```

Remove node cur:





Remove node `cur:`



Remove node `cur`:

- Searching the predecessor in $O(n)$

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
```




Getting a reference to node at `pos`:



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

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```
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
```



Searching a value:



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




Runtime:



Runtime:

- Singly linked list:



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 - `next` in $O(1)$



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- Better with `doubly linked lists`



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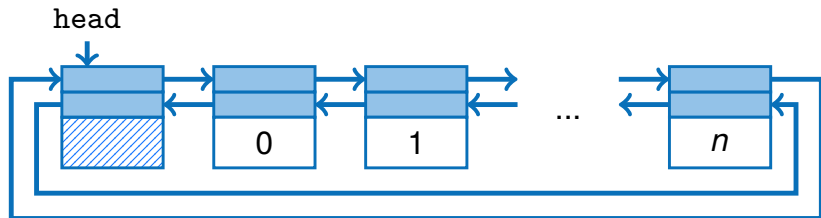
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 - a constant number of pointers needs to be modified
 - `lookup` in $\Theta(n)$
 - Even if the elements are sorted we can only retrieve them in $\Theta(n)$.
Why?

Linked list in book:



Linked Lists

List in real program



Linked list in memory:



Feedback

Exercises

Lecture

Sorted Sequences

Linked Lists

Binary Search Trees



Runtime of a search tree:



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- `lookup` in $O(\log n)$
 - The structure helps searching efficiently



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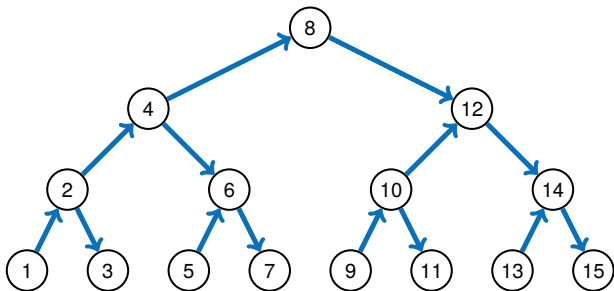


Figure: A binary search tree



Figure: Another binary search tree

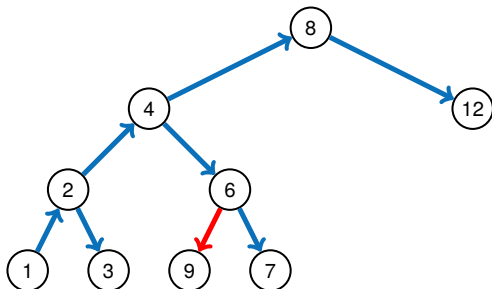


Figure: **Not** a binary search tree



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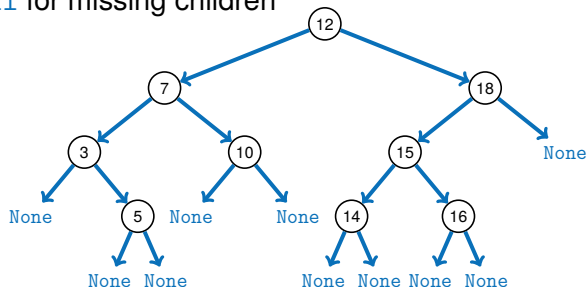


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Figure: Binary search tree with links



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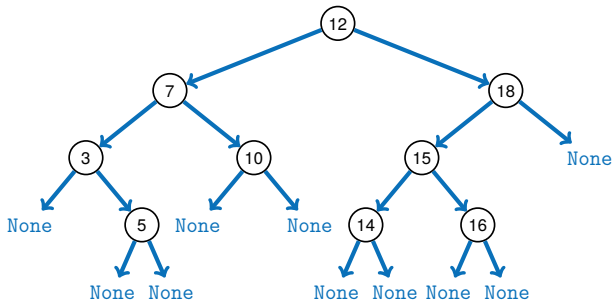
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■ `lookup(14)`

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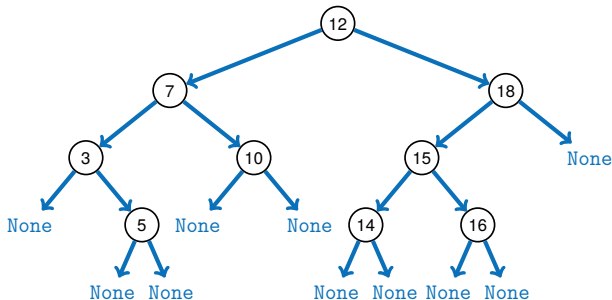
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Binary Search Trees

Implementation - Insert



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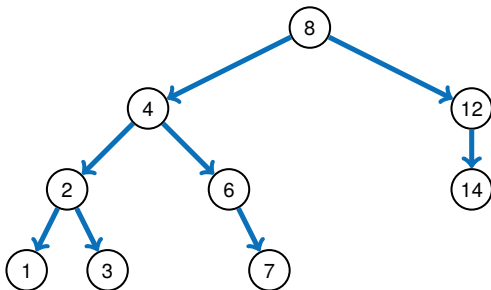


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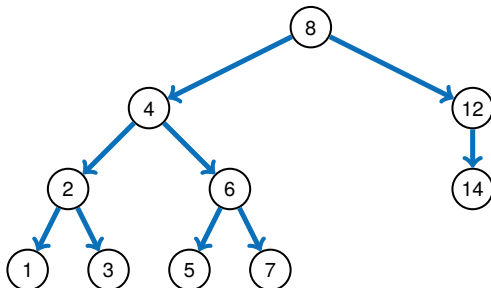


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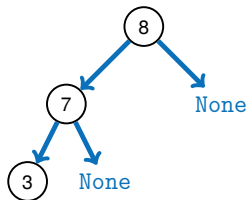


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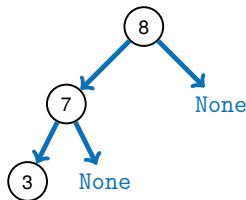


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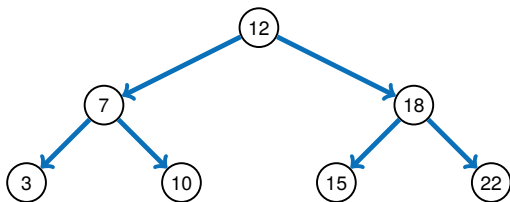


Figure: Complete binary tree $d = \log n$

■ 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`

■ **Binary Search Tree**

[Wik] [Binary search tree](#)

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