Algorithmns and Datastructures

Linked Lists, Binary Search Trees

Albert-Ludwigs-Universität Freiburg

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Bioinformatics Group / Department of Computer Science

Algorithmns and Datastructures, January 2017

Structure

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Feedback

- Exercises
- Lecture

Sorted Sequences

Linked Lists

Binary Search Trees

Feedback from the exercises

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- Missing support in forum

Feedback from the lecture

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- Lecture recordings are now password protected

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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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- How could we implement this?

Static array:

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  - We have to copy up to n elements

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- Lets have a closer look

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Binary Search Trees

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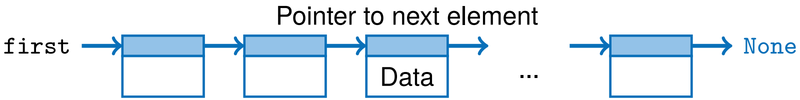

Figure: Linked list

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- 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
  $\Rightarrow$ We have to iterate over the list

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List with head / last element pointer:

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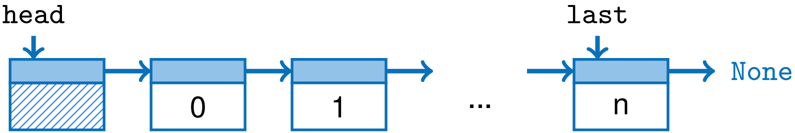

Figure: Singly linked list

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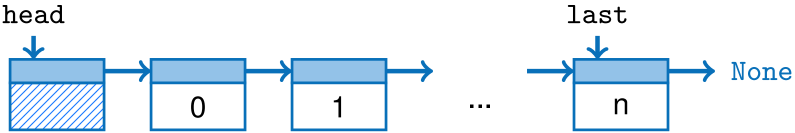

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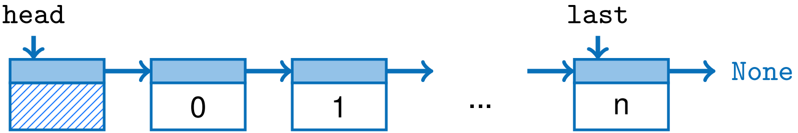

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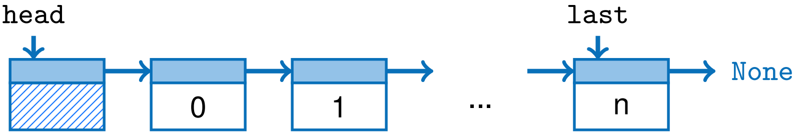

Figure: Singly linked list

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

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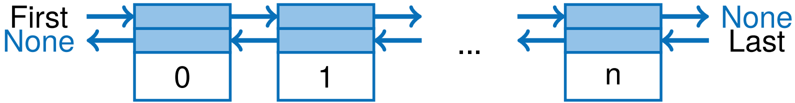

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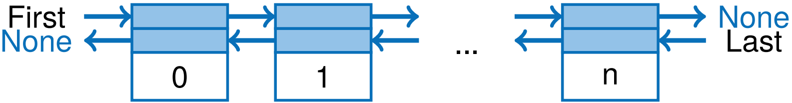

Figure: Doubly linked list

- Pointer to successor element

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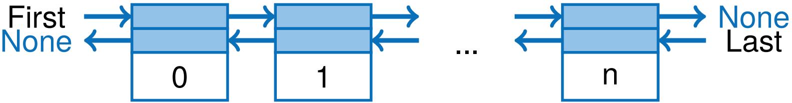

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- Pointer to successor element
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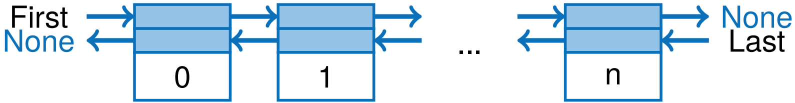

Figure: Doubly linked list

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

```
public class Listelem
```

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

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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)
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Linked Lists

Implementation - Node/Element - Java

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

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```java
//Function to read and write private fields
public int getData() {return data; }
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public Listelem getNext() { return next; }
public void setNext(Listelem n) { next = n; }
```

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    //Integer represents possible data, e.g.
    //self defined refence datatypes
}
```

```
class Listelem
{
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```
class Listelem
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private:
  int data;
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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; }
}
```

```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
```

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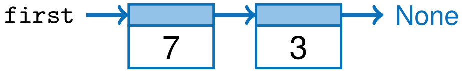
- `first.nextNode = Node(3)`



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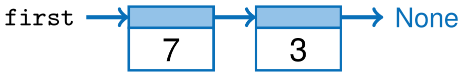
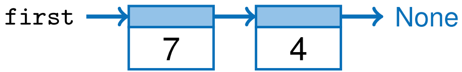
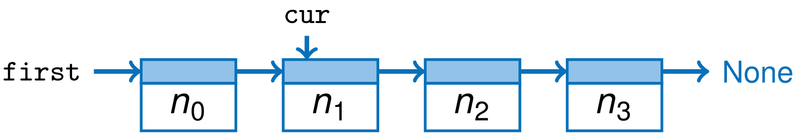


- `first.nextNode.value = 4`



Inserting a node after node `cur`:



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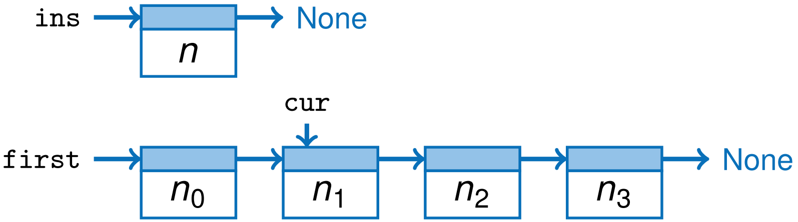

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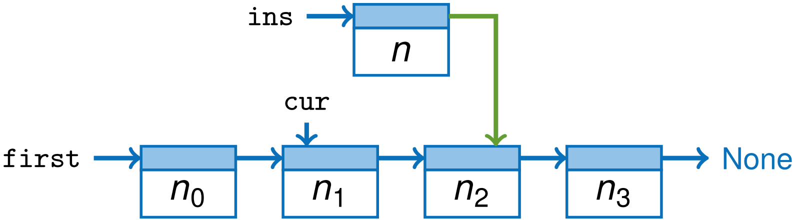

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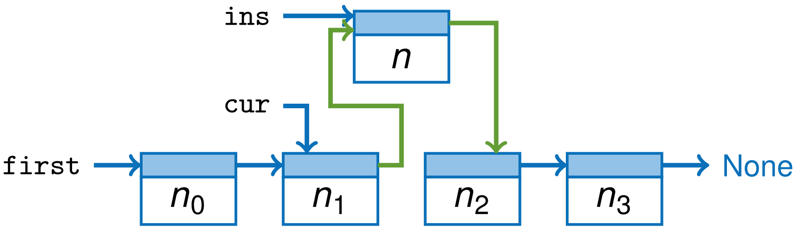

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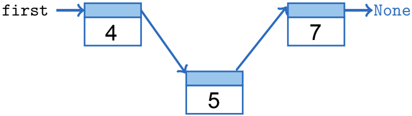

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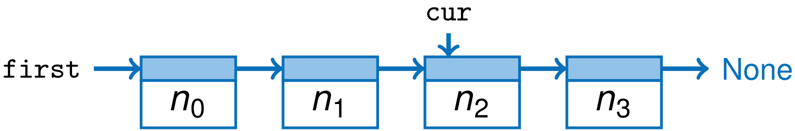

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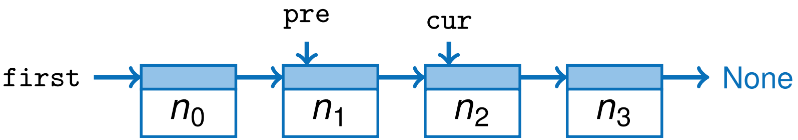

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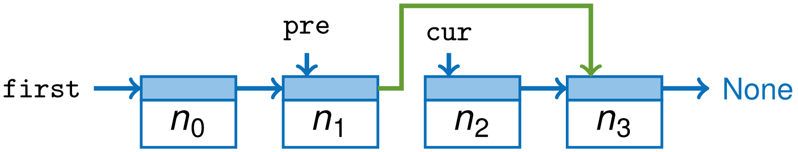

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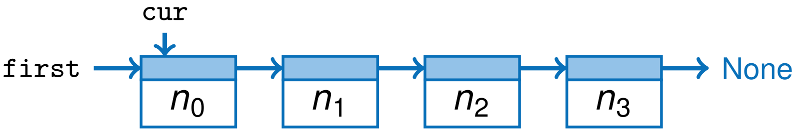

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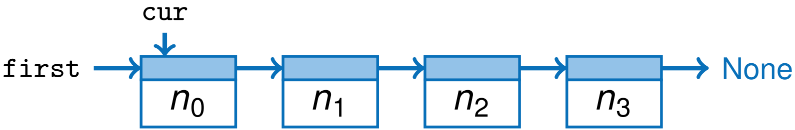

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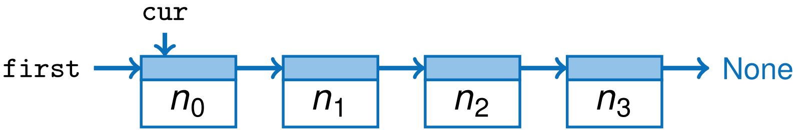

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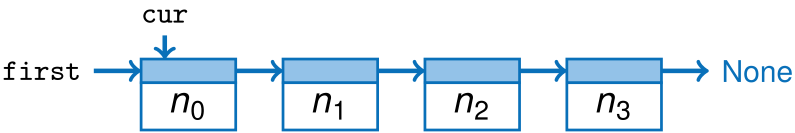

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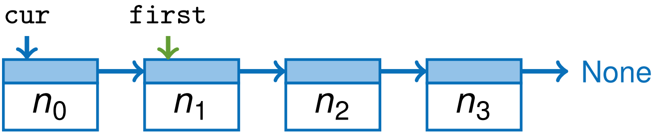

Removing a node `cur`: (General case)

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

    pre.nextNode = cur.nextNode
```

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- Disadvantage
  - We have to consider the first node at other operations

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  - Deleting the first node is no special case
- Disadvantage
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  - Iterating all nodes
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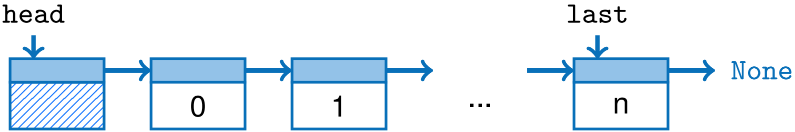

```
class LinkedList:
    def __init__(self):
        self.itemCount = 0
        self.head = Node()
        self.last = self.head

    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;
    }
```

```java
        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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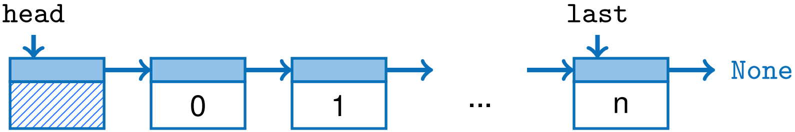

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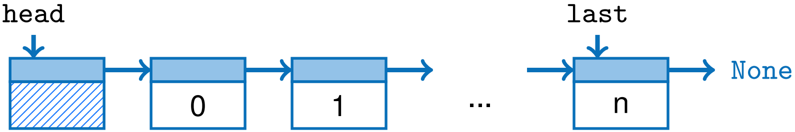

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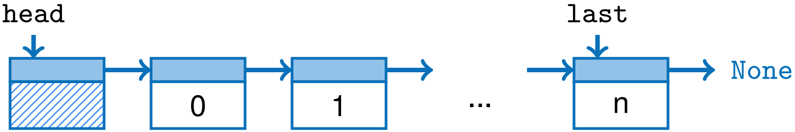

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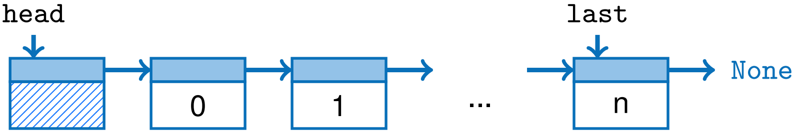

- `Head` points to the first node, `last` to the last node
- We can append elements to the end of the list in $O(1)$ through the `last` node
- We have to keep the pointer to `last` updated after all operations

Appending an element:

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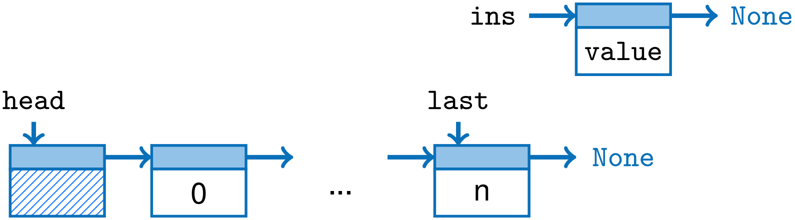

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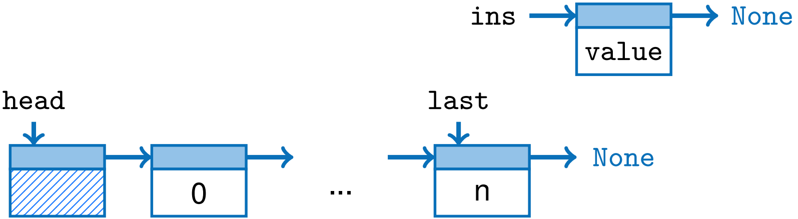
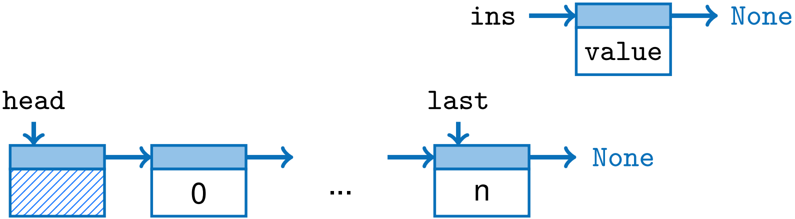


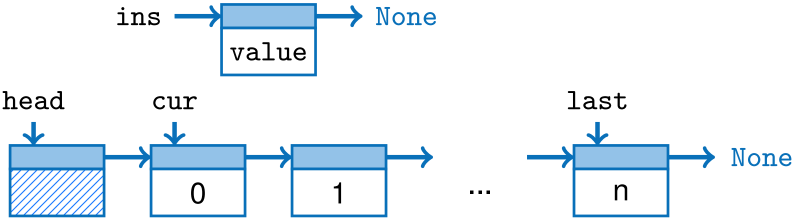

```
def append(self, value):
    last.nextNode = Node(value)
    last = last.NextNode
    itemCount += 1
```

Appending an element:




- ```python
  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`:

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Inserting after node `cur`:

- The pointer to `head` is not modified

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Inserting after node `cur`:

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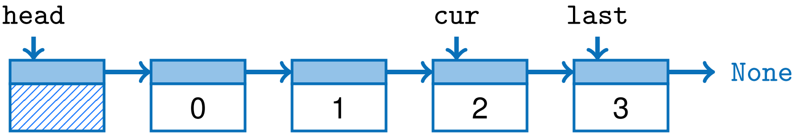
  def insertAfter(self, cur, value):
      if cur == last:
          # also update last node
          append(value)
      else:
          # last node is not modified
          cur.nextNode = Node(value, \
              cur.nextNode)
          itemCount += 1
  ```
  ```

Remove node `cur`:



Remove node `cur`:

Remove node `cur`:

- Searching the predecessor in $O(n)$

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- 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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- First element is head without an assigned value

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Searching a `value`:

- First element is head without an assigned 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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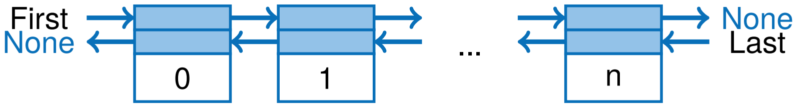

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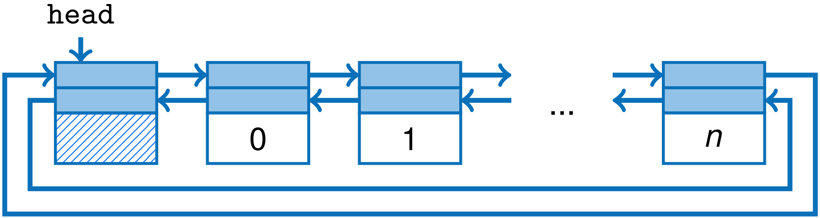

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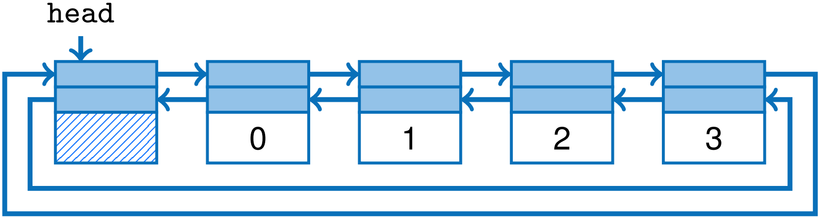
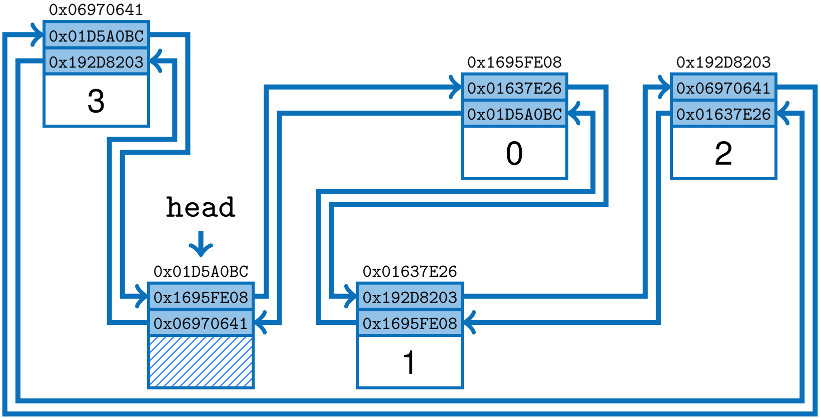
    - a constant number of pointers needs to be modified
  - `lookup` in $\Theta(n)$
    - Even if the elements are sorted we can only retrieve them in $\Theta(n)$.
      Why?

Linked list in book:



Linked list in memory:



Structure

Feedback

Exercises

Lecture

Sorted Sequences

Linked Lists

Binary Search Trees

Runtime of a search tree:

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- `next` and `previous` in $O(1)$

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- `next` and `previous` in $O(1)$
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- `insert` and `remove` in $O(log\ n)$
  - We will see why
- `lookup` in $O(log\ n)$
  - The structure helps searching efficiently

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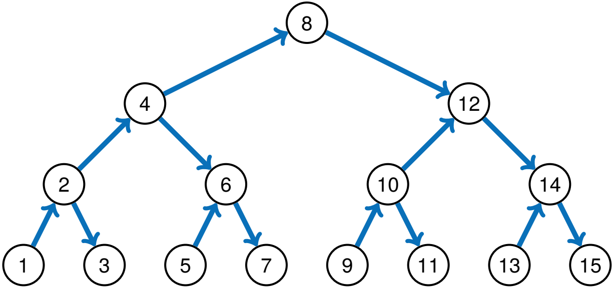

Figure: A binary search tree

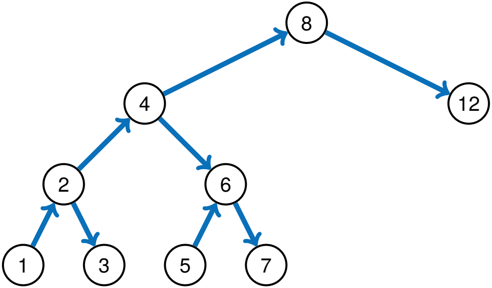

Figure: Another binary search tree

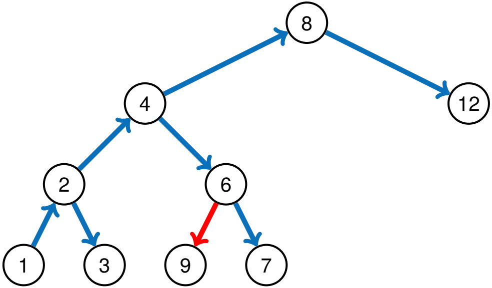

Figure: **Not** a binary search tree

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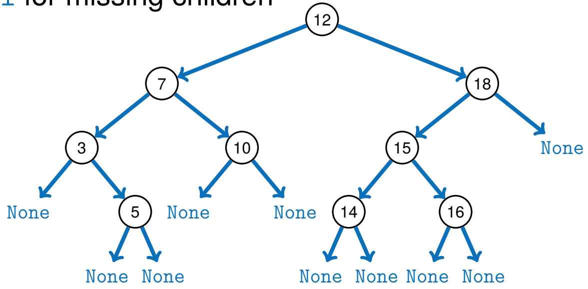

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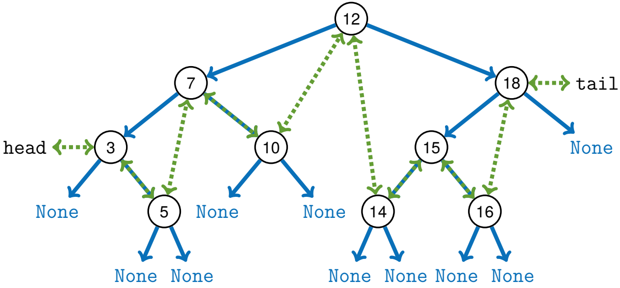

Figure: Binary search tree with links

Lookup:

Lookup:

- Definition:
  " Search the element with the given key. If no element is found return the element with the next (bigger) key. "

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

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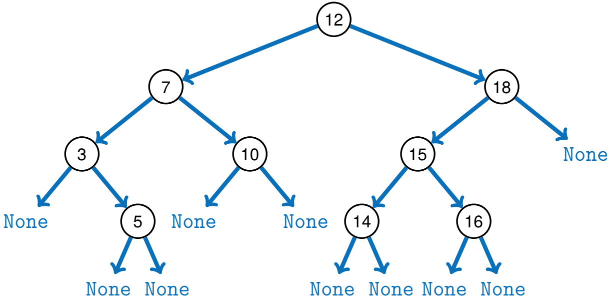

Examples:

Figure: Binary search tree with total order "<"

For each node applies the total order:

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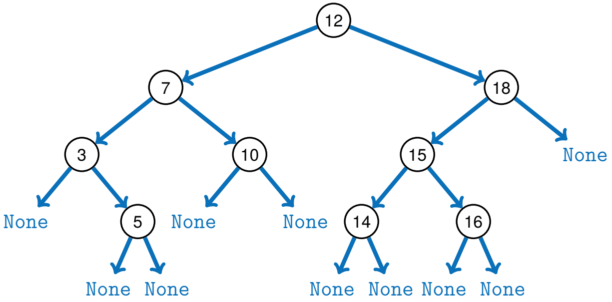

Figure: Binary search tree with total order “<”

Examples:

- `lookup(14)`

For each node applies the total order:

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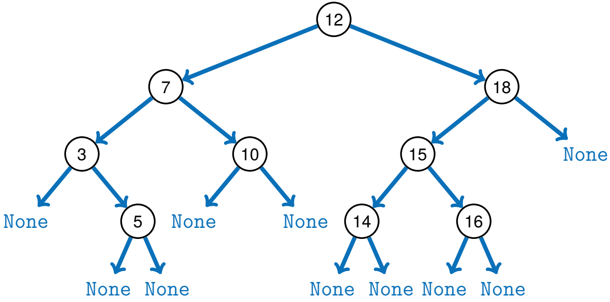

Figure: Binary search tree with total order "<"

Examples:

- `lookup(14)`
- `lookup(6)`

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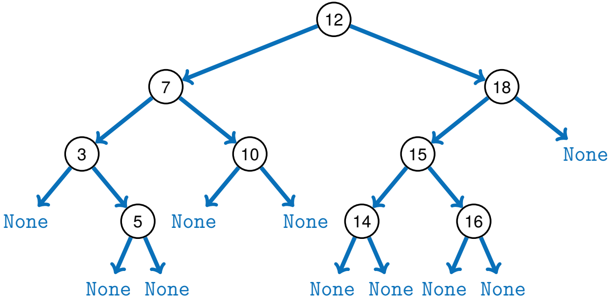

Figure: Binary search tree with total order “<”

Examples:

- `lookup(14)`
- `lookup(6)`
- `lookup(19)`

Insert:

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- We search for the key in our search tree

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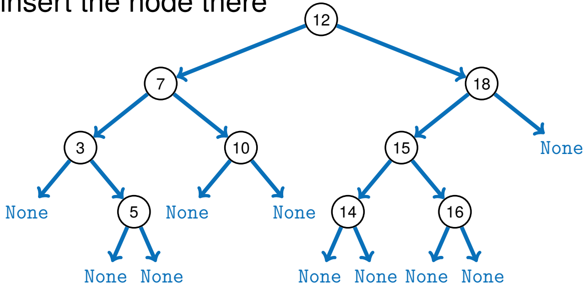

Figure: Binary search tree with total order "<"

Remove: Case 1: The node “5” has no children

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- Find parent of node “5” (“6”)

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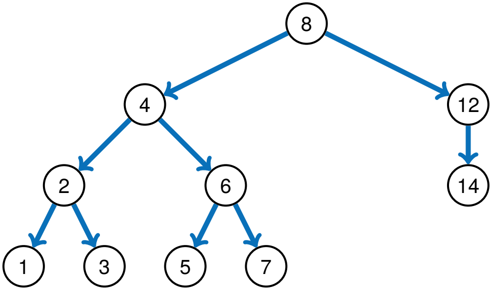

Figure: Binary search tree with total order “$<$”

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”

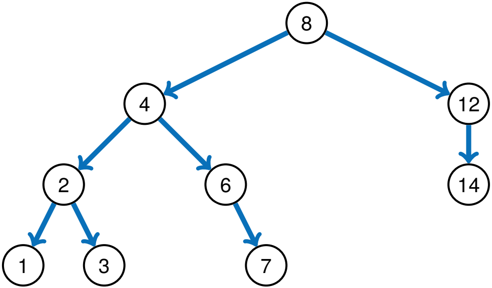

Figure: Binary search tree after deleting node “5”

Remove: Case 2: The node “12” has one child

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- Find the child of node “12” (“14”)

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- Find the child of node “12” (“14”)
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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”)

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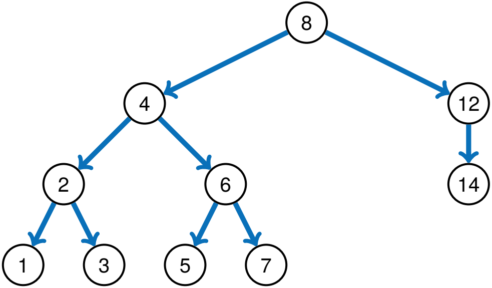

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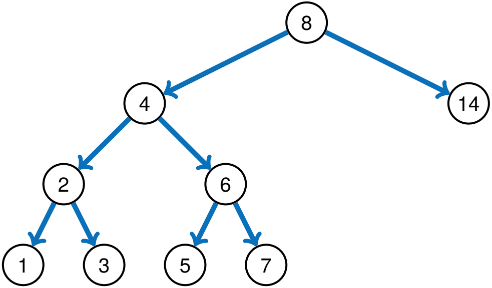

Figure: Binary search tree after delting node “12”

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

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- Find the successor of node “4” (“5”)

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- Find the successor of node “4” (“5”)
- Replace the value of node “4” with the value of node “5”

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- Find the successor of node “4” (“5”)
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- Delete node “5” (the successor of node “4”) with remove-case 1 or 2

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

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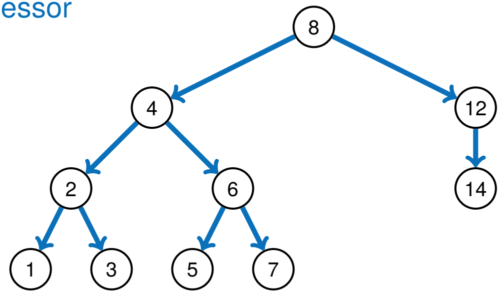
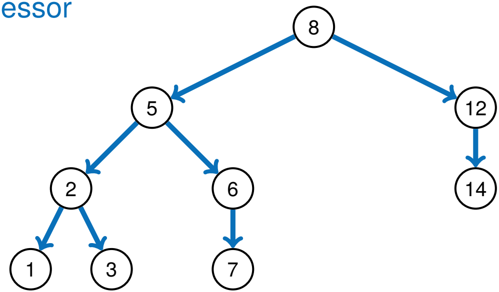


Remove: Case 3: The node “4” has two children

- 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



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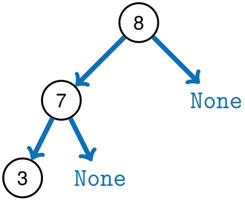

Figure: Degenerated binary tree $d = n$

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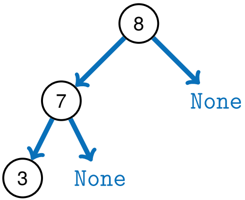

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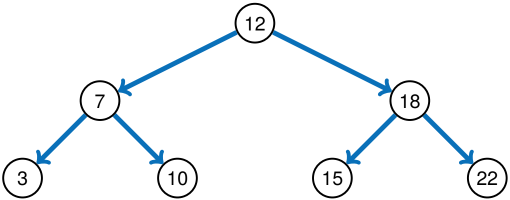

Figure: Complete binary tree $d = \log n$

- **General**

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- **Linked List**

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

- **Binary Search Tree**

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