DATA STRUCTURES AND ALGORITHMS
LECTURE 7

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2020 - 2021

In Lecture 6...

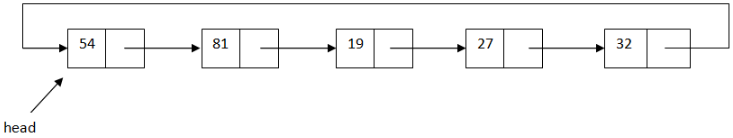
- Linked Lists
- Sorted Linked List

Today

- Linked List
    - Circular Lists
    - XOR Lists
    - Skip Lists
- Linked List on Array

Circular Lists

- For a SLL or a DLL the last node has as *next* the value *NIL*. In a *circular list* no node has *NIL* as next, since the last node contains the address of the first node in its next field.



Circular Lists

- We can have singly linked and doubly linked circular lists, in the following we will discuss the singly linked version.
- In a circular list each node has a successor, and we can say that the list does not have an end.
- We have to be careful when we iterate through a circular list, because we might end up with an infinite loop (if we set as stopping criterion the case when *currentNode* or *[currentNode].next* is *NIL*.
- There are problems where using a circular list makes the solution simpler (for example: Josephus circle problem, rotation of a list)

Circular Lists

- Operations for a circular list have to consider the following two important aspects:
    - The *last* node of the list is the one whose *next* field is the *head* of the list.
    - Inserting before the head, or removing the head of the list, is no longer a simple $\Theta(1)$ complexity operation, because we have to change the *next* field of the last node as well (and for this we have to find the last node).

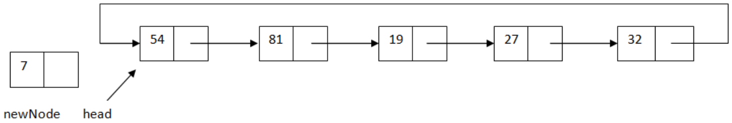
Circular Lists - Representation

- The representation of a circular list is exactly the same as the representation of a simple SLL. We have a structure for a *Node* and a structure for the *Circular Singly Linked Lists - CSLL*.

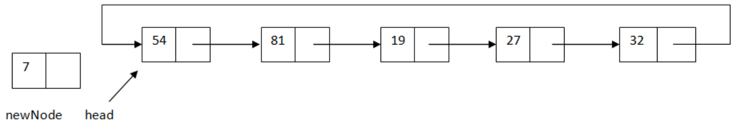
```
CSLLNode:
    info: TElem
    next: ↑ CSLLNode
```

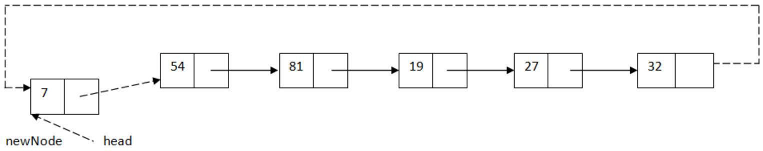
```
CSLL:
    head: ↑ CSLLNode
```

CSLL - InsertFirst



CSLL - InsertFirst





CSLL - InsertFirst

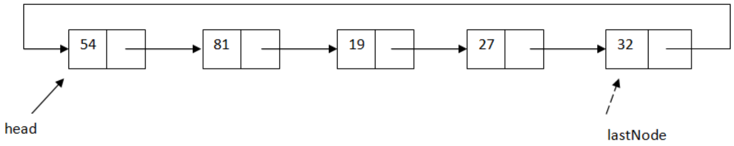
```
**subalgorithm** insertFirst (csll, elem) **is:**
//pre: csll is a CSLL, elem is a TElem
//post: the element elem is inserted at the beginning of csll
  newNode ← allocate()
  [newNode].info ← elem
  [newNode].next ← newNode
  if csll.head = NIL then
    csll.head ← newNode
  else
    lastNode ← csll.head
    while [lastNode].next ≠ csll.head execute
      lastNode ← [lastNode].next
    end-while
//continued on the next slide...
```

CSLL - InsertFirst

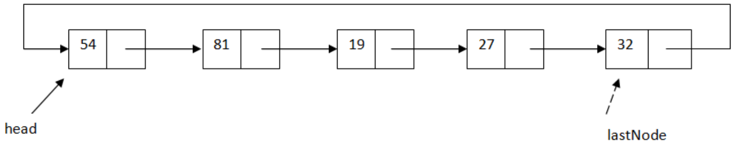
```
        [newNode].next ← csll.head
        [lastNode].next ← newNode
        csll.head ← newNode
    end-if
end-subalgorithm
```

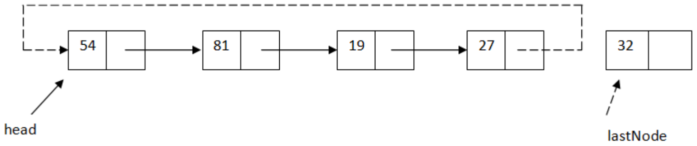
- Complexity: $\Theta(n)$
- Note: inserting a new element at the end of a circular list looks exactly the same, but we do not modify the value of *csll.head* (so the last instruction is not needed).

CSLL - DeleteLast



CSLL - DeleteLast





CSLL - DeleteLast

```
function deleteLast(csll) is:
//pre: csll is a CSLL
//post: the last element from csll is removed and the node
//containing it is returned
   deletedNode ← NIL
   if csll.head ≠ NIL then
      if [csll.head].next = csll.head then
         deletedNode ← csll.head
         csll.head ← NIL
      else
         prevNode ← csll.head
         while [[prevNode].next].next ≠ csll.head execute
            prevNode ← [prevNode].next
         end-while
//continued on the next slide...
```

```
      deletedNode ← [prev].next
      [prev].next ← csll.head
    end-if
  end-if
  [deletedNode].next ← NIL
  deleteLast ← deletedNode
end-function
```

- Complexity: $\Theta(n)$

CSLL - Iterator

- How can we define an iterator for a CSLL? What do you think is the most challenging part of implementing the iterator?

CSLL - Iterator

- How can we define an iterator for a CSLL? What do you think is the most challenging part of implementing the iterator?
- The main problem with the *standard* SLL iterator is its *valid* method. For a SLL *valid* returns false, when the value of the *currentElement* becomes *NIL*. But in case of a circular list, *currentElement* will never be *NIL*.
- We have finished iterating through all elements when the value of *currentElement* becomes equal to the *head* of the list.
- However, writing that the iterator is invalid when *currentElement* equals the *head*, will produce an iterator which is invalid the moment it was created.

CSLL - Iterator - Possibilities

- We can say that the iterator is invalid, when the *next* of the *currentElement* is equal to the *head* of the list.
- This will stop the iterator when it is set to the last element of the list, so if we want to print all the elements from a list, we have to call the *element* operation one more time when the iterator becomes invalid (or use a do-while loop instead of a while loop - but this causes problems when we iterate through an empty list).
- As a second problem, this violates the precondition that element should only be called when the iterator is valid.

CSLL - Iterator - Possibilities

- We can add a boolean flag to the iterator besides the *currentElement*, something that shows whether we are at the *head* for the first time (when the iterator was created), or whether we got back to the *head* after going through all the elements.

- For this version, standard iteration code remains the same.

CSLL - Iterator - Possibilities

- Similarly, if the CSLL contains a field for the size of the list, we can add a counter in the iterator (besides the current node), which counts how many times we called next. If it is equal to the size + 1, the iterator is invalid. It is a combination of how we represent current element for a dynamic array and a linked list.

- For this version, standard iteration code remains the same.

CSLL - Iterator - Possibilities

- Depending on the problem we want to solve, we might need a read/write iterator: one that can be used to change the content of the CSLL.
- We can have *insertAfter* - insert a new element after the current node - and *delete* - delete the current node
- We can say that the iterator is invalid when there are no elements in the circular list (especially if we delete from it).

The Josephus circle problem

- There are n men standing a circle waiting to be executed. Starting from one person we start counting into clockwise direction and execute the m^{th} person. After the execution we restart counting with the person after the executed one and execute again the m^{th} person. The process is continued until only one person remains: this person is freed.
- Given the number of men, n, and the number m, determine which person will be freed.
- For example, if we have 5 men and $m = 3$, the 4^{th} man will be freed.

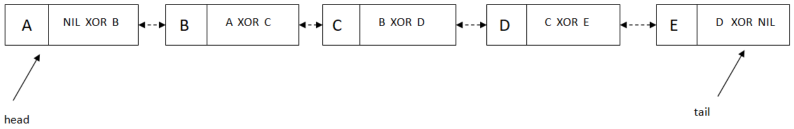
Circular Lists - Variations

- There are different possible variations for a circular list that can be useful, depending on what we use the circular list for.
    - Instead of retaining the *head* of the list, retain its *tail*. In this way, we have access both to the *head* and the *tail*, and can easily insert before the head or after the tail. Deleting the head is simple as well, but deleting the tail still needs $\Theta(n)$ time.
    - Use a *header* or *sentinel* node - a special node that is considered the *head* of the list, but which cannot be deleted or changed - it is simply a separation between the head and the tail. For this version, knowing when to stop with the iterator is easier.

XOR Linked List

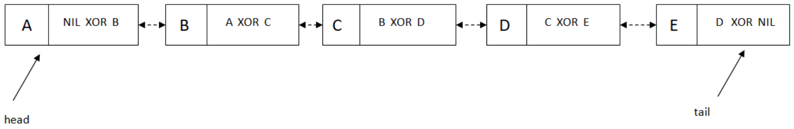
- Doubly linked lists are better than singly linked lists because they offer better complexity for some operations
- Their disadvantage is that they occupy more memory, because you have two links to memorize, instead of just one.
- A memory-efficient solution is to have a *XOR Linked List*, which is a doubly linked list (we can traverse it in both directions), where every node retains one single link, which is the XOR of the previous and the next node.

XOR Linked List - Example



- How do you traverse such a list?

XOR Linked List - Example



- How do you traverse such a list?
  - We start from the head (but we can have a backward traversal starting from the tail in a similar manner), the node with A
  - The address from node A is directly the address of node B (NIL XOR B = B)
  - When we have the address of node B, its link is A XOR C. To get the address of node C, we have to XOR B's link with the address of A (it's the previous node we come from): A XOR C XOR A = A XOR A XOR C = NIL XOR C = C

XOR Linked List - Representation

- We need two structures to represent a XOR Linked List: one for a node and one for the list

```
XORNode:
    info: TELem
    link: ↑ XORNode
```

```
XORList:
    head: ↑ XORNode
    tail: ↑ XORNode
```

XOR Linked List - Traversal

```
subalgorithm printListForward(xorl) is:
//pre: xorl is a XORList
//post: true (the content of the list was printed)
   prevNode ← NIL
   currentNode ← xorl.head
   while currentNode ≠ NIL execute
      write [currentNode].info
      nextNode ← prevNode XOR [currentNode].link
      prevNode ← currentNode
      currentNode ← nextNode
   end-while
end-subalgorithm
```

- Complexity: $\Theta(n)$

XOR Linked List - addToBeginning

- How can we add an element to the beginning of the list?

XOR Linked List - addToBeginning

- How can we add an element to the beginning of the list?

```
subalgorithm addToBeginning(xorl, elem) is:
//pre: xorl is a XORList
//post: a node with info elem was added to the beginning of the list
    newNode ← allocate()
    [newNode].info ← elem
    [newNode].link ← xorl.head
    if xorl.head = NIL then
        xorl.head ← newNode
        xorl.tail ← newNode
    else
        [xorl.head].link ← [xorl.head].link XOR newNode
        xorl.head ← newNode
    end-if
end-subalgorithm
```

- Complexity:

XOR Linked List - addToBeginning

- How can we add an element to the beginning of the list?

```
subalgorithm addToBeginning(xorl, elem) is:
//pre: xorl is a XORList
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    newNode ← allocate()
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        xorl.tail ← newNode
    else
        [xorl.head].link ← [xorl.head].link XOR newNode
        xorl.head ← newNode
    end-if
end-subalgorithm
```

- Complexity: $\Theta(1)$

Skip Lists

- Assume that we want to memorize a sequence of sorted elements. The elements can be stored in:
  - dynamic array
  - linked list (let's say doubly linked list)
- We know that the most frequently used operation will be the insertion of a new element, so we want to choose a data structure for which insertion has the best complexity. Which one should we choose?

Skip Lists

- We can divide the insertion operation into two steps: *finding where to insert* and *inserting the elements*

Skip Lists

- We can divide the insertion operation into two steps: *finding where to insert* and *inserting the elements*
  - For a dynamic array finding the position can be optimized (binary search $O(log_2 n)$), but the insertion is $O(n)$
  - For a linked list the insertion is optimal ($\Theta(1)$), but finding where to insert is $O(n)$

Skip List

- A skip list is a data structure that allows *fast search* in an ordered sequence.
- How can we do that?

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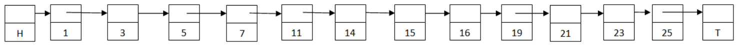
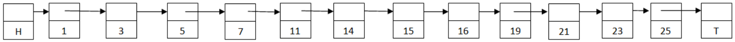


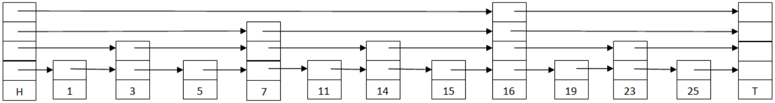
Skip List

- A skip list is a data structure that allows *fast search* in an ordered sequence.
- How can we do that?



  - Starting from an ordered linked list, we add to every second node another pointer that skips over one element.
  - We add to every fourth node another pointer that skips over 3 elements.
  - etc.

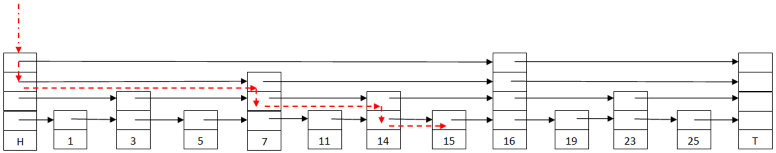
Skip List



- H and T are two special nodes, representing *head* and *tail*. They cannot be deleted, they exist even in an empty list.

Skip List - Search

- Search for element 15.



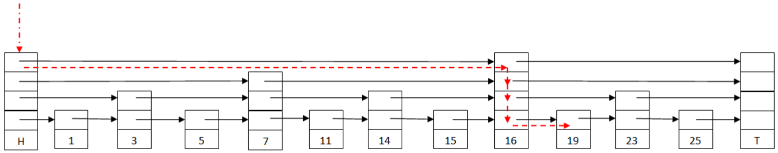
- Start from head and from highest level.
- If possible, go right.
- If cannot go right (next element is greater), go down a level.

Skip List

- Lowest level has all n elements.
- Next level has $\frac{n}{2}$ elements.
- Next level has $\frac{n}{4}$ elements.
- etc.
- $\Rightarrow$ there are approx $log_2 n$ levels.
- From each level, we check at most 2 nodes.
- Complexity of search: $O(log_2 n)$

Skip List - Insert

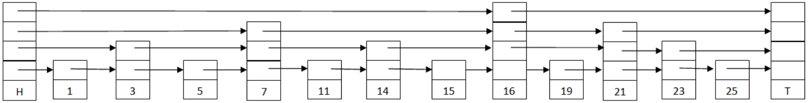
- Insert element 21.



- How *high* should the new node be?

Skip List - Insert

- *Height* of a new node is determined *randomly*, but in such a way that approximately half of the nodes will be on level 2, a quarter of them on level 3, etc.



- Assume we randomly generate the height 3 for the node with 21.

Skip List

- Skip Lists are *probabilistic* data structures, since we decide randomly the height of a newly inserted node.
- There might be a worst case, where every node has height 1 (so it is just a linked list).
- In practice, they function well.

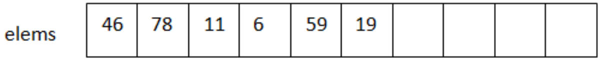
Linked Lists on Arrays

- What if we need a linked list, but we are working in a programming language that does not offer pointers (or references)?

- We can still implement linked data structures, without the explicit use of pointers or memory addresses, simulating them using arrays and array indexes.

Linked Lists on Arrays

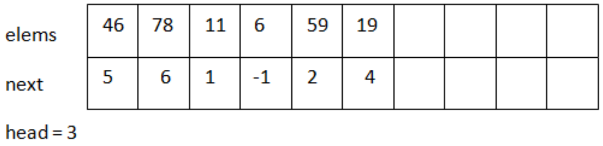
- Usually, when we work with arrays, we store the elements in the array starting from the leftmost position and place them one after the other (no empty spaces in the middle of the list are allowed).
- The order of the elements is given by the order in which they are placed in the array.



- Order of the elements: 46, 78, 11, 6, 59, 19

Linked Lists on Arrays

- We can define a linked data structure on an array, if we consider that the order of the elements is not given by their relative positions in the array, but by an integer number associated with each element, which shows the index of the next element in the array (thus we have a singly linked list).



elems	46	78	11	6	59	19				
next	5	6	1	-1	2	4				

head = 3

- Order of the elements: 11, 46, 59, 78, 19, 6

Linked Lists on Arrays

- Now, if we want to delete the number 46 (which is actually the second element of the list), we do not have to move every other element to the left of the array, we just need to modify the links:

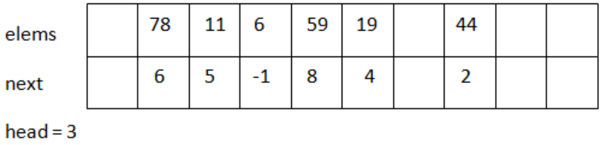
elems		78	11	6	59	19				
next		6	5	-1	2	4				

head = 3

- Order of the elements: 11, 59, 78, 19, 6

Linked Lists on Arrays

- If we want to insert a new element, for example 44, at the 3^{rd} position in the list, we can put the element anywhere in the array, the important part is setting the links correctly:



elems		78	11	6	59	19		44		
next		6	5	-1	8	4		2		

head = 3

- Order of the elements: 11, 59, 44, 78, 19, 6

Linked Lists on Arrays

- When a new element needs to be inserted, it can be put to any empty position in the array. However, finding an empty position has $O(n)$ complexity, which will make the complexity of any insert operation (anywhere in the list) $O(n)$. In order to avoid this, we will keep a linked list of the empty positions as well.

elems		78	11	6	59	19		44		
next	7	6	5	-1	8	4	9	2	10	-1

head = 3

firstEmpty = 1

Linked Lists on Arrays

- In a more formal way, we can simulate a singly linked list on an array with the following:
    - an array in which we will store the elements.
    - an array in which we will store the links (indexes to the next elements).
    - the capacity of the arrays (the two arrays have the same capacity, so we need only one value).
    - an index to tell where the *head* of the list is.
    - an index to tell where the first empty position in the array is.

SLL on Array - Representation

- The representation of a singly linked list on an array is the following:

```
SLLA:
    elems: TElem[]
    next: Integer[]
    cap: Integer
    head: Integer
    firstEmpty: Integer
```

SLLA - Operations

- We can implement for a SLLA any operation that we can implement for a SLL:
  - insert at the beginning, end, at a position, before/after a given value
  - delete from the beginning, end, from a position, a given element
  - search for an element
  - get an element from a position

SLLA - Init

```
subalgorithm init(slla) is:
//pre: true; post: slla is an empty SLLA
  slla.cap ← INIT_CAPACITY
```

SLLA - Init

```
subalgorithm init(slla) is:
//pre: true; post: slla is an empty SLLA
   slla.cap ← INIT_CAPACITY
   slla.elems ← @an array with slla.cap positions
   slla.next ← @an array with slla.cap positions
   slla.head ← -1
   for i ← 1, slla.cap-1 execute
      slla.next[i] ← i + 1
   end-for
   slla.next[slla.cap] ← -1
   slla.firstEmpty ← 1
end-subalgorithm
```

- Complexity:

SLLA - Init

```
subalgorithm init(slla) is:
//pre: true; post: slla is an empty SLLA
   slla.cap ← INIT_CAPACITY
   slla.elems ← @an array with slla.cap positions
   slla.next ← @an array with slla.cap positions
   slla.head ← -1
   for i ← 1, slla.cap-1 execute
      slla.next[i] ← i + 1
   end-for
   slla.next[slla.cap] ← -1
   slla.firstEmpty ← 1
end-subalgorithm
```

- Complexity: $\Theta(n)$ -where n is the initial capacity

SLLA - Search

```
function search (slla, elem) is:
//pre: slla is a SLLA, elem is a TElem
//post: return True is elem is in slla, False otherwise
   current ← slla.head
   while current $\neq$ -1 and slla.elems[current] $\neq$ elem execute
      current ← slla.next[current]
   end-while
   if current $\neq$ -1 then
      search ← True
   else
      search ← False
   end-if
end-function
```

- Complexity:

SLLA - Search

```
function search (slla, elem) is:
//pre: slla is a SLLA, elem is a TElem
//post: return True is elem is in slla, False otherwise
   current ← slla.head
   while current $\neq$ -1 and slla.elems[current] $\neq$ elem execute
      current ← slla.next[current]
   end-while
   if current $\neq$ -1 then
      search ← True
   else
      search ← False
   end-if
end-function
```

- Complexity: $O(n)$

SLLA - Search

- From the *search* function we can see how we can go through the elements of a SLLA (and how similar this traversal is to the one done for a SLL):
    - We need a *current* element used for traversal, which is initialized to the index of the *head* of the list.
    - We stop the traversal when the value of *current* becomes -1
    - We go to the next element with the instruction: *current* $\leftarrow$ *slla.next[current]*.

SLLA - InsertFirst

```
subalgoritm insertFirst(slla, elem) is:
//pre: slla is an SLLA, elem is a TElem
//post: the element elem is added at the beginning of slla
  if slla.firstEmpty = -1 then
    newElems ← @an array with slla.cap * 2 positions
    newNext ← @an array with slla.cap * 2 positions
    for i ← 1, slla.cap execute
      newElems[i] ← slla.elems[i]
      newNext[i] ← slla.next[i]
    end-for
    for i ← slla.cap + 1, slla.cap*2 - 1 execute
      newNext[i] ← i + 1
    end-for
    newNext[slla.cap*2] ← -1
//continued on the next slide...
```

SLLA - InsertFirst

```
        //free slla.elems and slla.next if necessary
        slla.elems ← newElems
        slla.next ← newNext
        slla.firstEmpty ← slla.cap+1
        slla.cap ← slla.cap * 2
    **end-if**
    newPosition ← slla.firstEmpty
    slla.elems[newPosition] ← elem
    slla.firstEmpty ← slla.next[slla.firstEmpty]
    slla.next[newPosition] ← slla.head
    slla.head ← newPosition
**end-subalgorithm**
```

- Complexity:

SLLA - InsertFirst

```
        //free slla.elems and slla.next if necessary
        slla.elems ← newElems
        slla.next ← newNext
        slla.firstEmpty ← slla.cap+1
        slla.cap ← slla.cap * 2
    **end-if**
    newPosition ← slla.firstEmpty
    slla.elems[newPosition] ← elem
    slla.firstEmpty ← slla.next[slla.firstEmpty]
    slla.next[newPosition] ← slla.head
    slla.head ← newPosition
**end-subalgorithm**
```

- Complexity: $\Theta(1)$ amortized

SLLA - DeleteElement

```
subalgorithm deleteElement(slla, elem) is:
//pre: slla is a SLLA; elem is a TElem
//post: the element elem is deleted from SLLA
    nodC ← slla.head
    prevNode ← -1
    while nodC $\neq$ -1 and slla.elems[nodC] $\neq$ elem execute
        prevNode ← nodC
        nodC ← slla.next[nodC]
    end-while
    if nodC $\neq$ -1 then
        if nodC = slla.head then
            slla.head ← slla.next[slla.head]
        else
            slla.next[prevNode] ← slla.next[nodC]
        end-if
//continued on the next slide...
```

SLLA - DeleteElement

```
//add the nodC position to the list of empty spaces
        slla.next[nodC] ← slla.firstEmpty
        slla.firstEmpty ← nodC
    else
        @the element does not exist
    end-if
end-subalgorithm
```

- Complexity: $O(n)$

SLLA - Iterator

- Iterator for a SSLA is a combination of an iterator for an array and of an iterator for a singly linked list:
- Since the elements are stored in an array, the *currentElement* will be an index from the array.
- But since we have a linked list, going to the next element will not be done by incrementing the *currentElement* by one; we have to follow the *next* links.
- Also, initialization will be done with the position of the head, not position 1.

DLLA

- Obviously, we can define a doubly linked list as well without pointers, using arrays.
- For the DLLA we will see another way of representing a linked list on arrays:
    - The main idea is the same, we will use array indexes as links between elements
    - We are using the same information, but we are going to structure it differently
    - However, we can make it look more similar to linked lists with dynamic allocation

DLLA - Node

- Linked Lists with dynamic allocation are made of nodes. We can define a structure to represent a node, even if we are working with arrays.
- A node (for a doubly linked list) contains the information and links towards the previous and the next nodes:

```
DLLANode:
    info: TElem
    next: Integer
    prev: Integer
```

DLLA

- Having defined the *DLLANode* structure, we only need one array, which will contain *DLLANodes*.
- Since it is a doubly linked list, we keep both the head and the tail of the list.

```
DLLA:
    nodes: DLLANode[]
    cap: Integer
    head: Integer
    tail: Integer
    firstEmpty: Integer
    size: Integer //it is not mandatory, but useful
```

DLLA - Allocate and free

- To make the representation and implementation even more similar to a dynamically allocated linked list, we can define the *allocate* and *free* functions as well.

```
function allocate(dlla) is:
//pre: dlla is a DLLA
//post: a new element will be allocated and its position returned
    newElem $\leftarrow$ dlla.firstEmpty
    if newElem $\neq$ -1 then
        dlla.firstEmpty $\leftarrow$ dlla.nodes[dlla.firstEmpty].next
        if dlla.firstEmpty $\neq$ -1 then
            dlla.nodes[dlla.firstEmpty].prev $\leftarrow$ -1
        end-if
        dlla.nodes[newElem].next $\leftarrow$ -1
        dlla.nodes[newElem].prev $\leftarrow$ -1
    end-if
    allocate $\leftarrow$ newElem
end-function
```

DLLA - Allocate and free

```
subalgorithm free (dlla, poz) is:
//pre: dlla is a DLLA, poz is an integer number
//post: the position poz was freed
   dlla.nodes[poz].next ← dlla.firstEmpty
   dlla.nodes[poz].prev ← -1
   if dlla.firstEmpty ≠ -1 then
      dlla.nodes[dlla.firstEmpty].prev ← poz
   end-if
   dlla.firstEmpty ← poz
end-subalgorithm
```

DLLA - InsertPosition

```
subalgorithm insertPosition(dlla, elem, poz) is:
//pre: dlla is a DLLA, elem is a TElem, poz is an integer number
//post: the element elem is inserted in dlla at position poz
   if poz < 1 OR poz > dlla.size + 1 execute
      @throw exception
   end-if
   newElem ← alocate(dlla)
   if newElem = -1 then
      @resize
      newElem ← alocate(dlla)
   end-if
   dlla.nodes[newElem].info ← elem
   if poz = 1 then
      if dlla.head = -1 then
         dlla.head ← newElem
         dlla.tail ← newElem
      else
//continued on the next slide...
```

DLLA - InsertPosition

```
        dlla.nodes[newElem].next $\leftarrow$ dlla.head
        dlla.nodes[dlla.head].prev $\leftarrow$ newElem
        dlla.head $\leftarrow$ newElem
    **end-if**
  **else**
    nodC $\leftarrow$ dlla.head
    pozC $\leftarrow$ 1
    **while** nodC $\neq$ -1 **and** pozC $<$ poz - 1 **execute**
        nodC $\leftarrow$ dlla.nodes[nodC].next
        pozC $\leftarrow$ pozC $+$ 1
    **end-while**
    **if** nodC $\neq$ -1 **then** //*it should never be -1, the position is correct*
        nodNext $\leftarrow$ dlla.nodes[nodC].next
        dlla.nodes[newElem].next $\leftarrow$ nodNext
        dlla.nodes[newElem].prev $\leftarrow$ nodC
        dlla.nodes[nodC].next $\leftarrow$ newElem
//*continued on the next slide...*
```

DLLA - InsertPosition

```
            if nodNext = -1 then
                dlla.tail ← newElem
            else
                dlla.nodes[nodNext].prev ← newElem
            end-if
        end-if
    end-if
end-subalgorithm
```

- Complexity: $O(n)$

DLLA - Iterator

- The iterator for a DLLA contains as *current element* the index of the current node from the array.

```
DLLAIterator:
    list: DLLA
    currentElement: Integer
```

DLLAIterator - init

```
subalgorithm init(it, dlla) is:
//pre: dlla is a DLLA
//post: it is a DLLAIterator for dlla
   it.list ← dlla
   it.currentElement ← dlla.head
end-subalgorithm
```

- For a (dynamic) array, currentElement is set to 0 when an iterator is created. For a DLLA we need to set it to the head of the list (which might be position 0, but it might be a different position as well).

- Complexity:

DLLAIterator - init

```
**subalgorithm** init(it, dlla) **is:**
//pre: dlla is a DLLA
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   it.list ← dlla
   it.currentElement ← dlla.head
**end-subalgorithm**
```

- For a (dynamic) array, currentElement is set to 0 when an iterator is created. For a DLLA we need to set it to the head of the list (which might be position 0, but it might be a different position as well).

- Complexity: $\Theta(1)$

DLLAIterator - getCurrent

```
subalgorithm getCurrent(it) is:
//pre: it is a DLLAIterator, it is valid
//post: e is a TElem, e is the current element from it
//throws exception if the iterator is not valid
   if it.currentElement = -1 then
      @throw exception
   end-if
   getCurrent ← it.list.nodes[it.currentElement].info
end-subalgorithm
```

- Complexity:

DLLAIterator - getCurrent

```
subalgorithm getCurrent(it) is:
//pre: it is a DLLAIterator, it is valid
//post: e is a TElem, e is the current element from it
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   if it.currentElement = -1 then
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   end-if
   getCurrent ← it.list.nodes[it.currentElement].info
end-subalgorithm
```

- Complexity: $\Theta(1)$

DLLAIterator - next

```
subalgoritm next (it) is:
//pre: it is a DLLAIterator, it is valid
//post: the current elements from it is moved to the next element
//throws exception if the iterator is not valid
  if it.currentElement = -1 then
    @throw exception
  end-if
  it.currentElement ← it.list.nodes[it.currentElement].next
end-subalgorithm
```

- In case a (dynamic) array, going to the next element means incrementing the *currentElement* by one. For a DLLA we need to follow the links.
- Complexity:

DLLAIterator - next

```
subalgoritm next (it) is:
//pre: it is a DLLAIterator, it is valid
//post: the current elements from it is moved to the next element
//throws exception if the iterator is not valid
    if it.currentElement = -1 then
        @throw exception
    end-if
    it.currentElement ← it.list.nodes[it.currentElement].next
end-subalgorithm
```

- In case a (dynamic) array, going to the next element means incrementing the *currentElement* by one. For a DLLA we need to follow the links.
- Complexity: $\Theta(1)$

DLLAIterator - valid

```
function valid (it) is:
//pre: it is a DLLAIterator
//post: valid return true is the current element is valid, false otherwise
  if it.currentElement = -1 then
    valid ← False
  else
    valid ← True
  end-if
end-function
```

- Complexity:

DLLAIterator - valid

```
function valid (it) is:
//pre: it is a DLLAIterator
//post: valid return true is the current element is valid, false otherwise
  if it.currentElement = -1 then
    valid ← False
  else
    valid ← True
  end-if
end-function
```

- Complexity: $\Theta(1)$