DATA STRUCTURES AND ALGORITHMS
LECTURE 5

Lect. PhD. Oneț-Marian Zsuzsanna

Babeș - Bolyai University
Computer Science and Mathematics Faculty

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In Lecture 4...

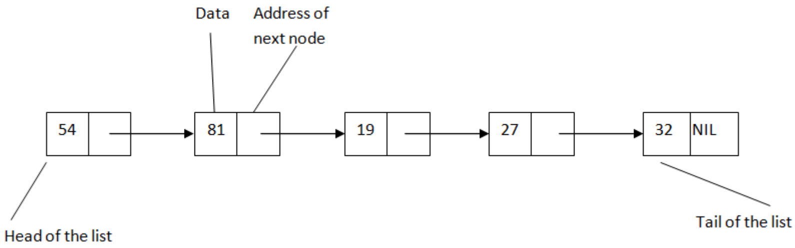
- Containers
  - ADT Priority Queue
  - ADT Deque
  - ADT List

  - Singly linked list

Today

- Singly linked list iterator
- Doubly linked list
- Sorted list
- Circular list

- Example of a singly linked list with 5 nodes:



- For the representation of a SLL we need two structures: one structure for the node and one for the list itself.

<u>SLLNode:</u>
  info: TElem *//the actual information*
  next: $\uparrow$ SLLNode *//address of the next node*

- For the representation of a SLL we need two structures: one structure for the node and one for the list itself.

SLLNode:
  info: TElem *//the actual information*
  next: ↑ SLLNode *//address of the next node*

SLL:
  head: ↑ SLLNode *//address of the first node*

- Usually, for a SLL, we only memorize the address of the head. However, there might be situations when we memorize the address of the tail as well (if it helps us implement the operations).

SLL - Iterator

- How can we define an iterator for a SLL?
- Remember, an iterator needs a reference to a *current element* from the data structure it iterates over. How can we denote a *current element* for a SLL?

SLL - Iterator

- How can we define an iterator for a SLL?
- Remember, an iterator needs a reference to a *current element* from the data structure it iterates over. How can we denote a *current element* for a SLL?
- Remember, for the dynamic array the current element was the index of the element. Can we do the same here?

- In case of a SLL, the current element from the iterator is actually a node of the list.

SLLIterator:
list: SLL
currentElement: ↑ SLLNode

SLL - Iterator - init operation

- What should the *init* operation do?

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subalgorithm init(it, sll) **is:**
//pre: sll is a SLL
//post: it is a SLLIterator over sll
  it.sll ← sll
  it.currentElement ← sll.head
end-subalgorithm

- Complexity:

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- Complexity: $\Theta(1)$

- What should the *getCurrent* operation do?

SLL - Iterator - getCurrent operation

- What should the *getCurrent* operation do?

function getCurrent(it) **is:**
//pre: it is a SLLIterator, it is valid
//post: getCurrent ← e, e is TElem, the current element from it
//throws: exception if it is not valid
  if it.currentElement = NIL **then**
    @throw an exception
  end-if
  e ← [it.currentElement].info
  getCurrent ← e
end-function

- Complexity:

SLL - Iterator - getCurrent operation

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- Complexity: $\Theta(1)$

SLL - Iterator - next operation

- What should the *next* operation do?

SLL - Iterator - next operation

- What should the *next* operation do?

subalgorithm next(it) **is:**
//pre: it is a SLLIterator, it is valid
//post: it' is a SLLIterator, the current element from it' refers to the next element
//throws: exception if it is not valid
  if it.currentElement = NIL **then**
    @throw an exception
  end-if
  it.currentElement ← [it.currentElement].next
end-subalgorithm

- Complexity:

- What should the *next* operation do?

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//pre: it is a SLLIterator, it is valid
//post: it' is a SLLIterator, the current element from it' refers to the next element
//throws: exception if it is not valid
  if it.currentElement = NIL **then**
    @throw an exception
  end-if
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end-subalgorithm

- Complexity: $\Theta(1)$

SLL - Iterator - valid operation

- What should the *valid* operation do?

SLL - Iterator - valid operation

- What should the *valid* operation do?

```
function valid(it) is:
//pre: it is a SLLIterator
//post: true if it is valid, false otherwise
  if it.currentElement ≠ NIL then
    valid ← True
  else
    valid ← False
  end-if
end-subalgorithm
```

- Complexity:

SLL - Iterator - valid operation

- What should the *valid* operation do?

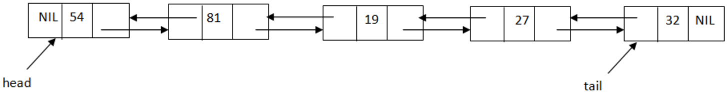
function valid(it) **is:**
//pre: it is a SLLIterator
//post: true if it is valid, false otherwise
  if it.currentElement $\neq$ NIL **then**
    valid $\leftarrow$ True
  else
    valid $\leftarrow$ False
  end-if
end-subalgorithm

- Complexity: $\Theta(1)$

Doubly Linked Lists - DLL

- A doubly linked list is similar to a singly linked list, but the nodes have references to the address of the previous node as well (besides the *next* link, we have a *prev* link as well).
- If we have a node from a DLL, we can go to the next node or to the previous one: we can walk through the elements of the list in both directions.
- The *prev* link of the first element is set to *NIL* (just like the *next* link of the last element).

Example of a Doubly Linked List



- Example of a doubly linked list with 5 nodes.

Doubly Linked List - Representation

- For the representation of a DLL we need two structures: one struture for the node and one for the list itself.

<u>DLLNode:</u>
  info: TElem
  next: ↑ DLLNode
  prev: ↑ DLLNode

- For the representation of a DLL we need two structures: one struture for the node and one for the list itself.

DLLNode:
  info: TElem
  next: ↑ DLLNode
  prev: ↑ DLLNode

DLL:
  head: ↑ DLLNode
  tail: ↑ DLLNode

DLL - Operations

- We can have the same operations on a DLL that we had on a SLL:
  - search for an element with a given value
  - add an element (to the beginning, to the end, to a given position, etc.)
  - delete an element (from the beginning, from the end, from a given positions, etc.)
  - get an element from a position
- Some of the operations have the exact same implementation as for SLL (e.g. search, get element), others have similar implementations. In general, if the structure of the list needs to be modified, we need to modify more links and have to pay attention to the *tail* node.

DLL - Insert at the end

- Inserting a new element at the end of a DLL is simple, because we have the *tail* of the list, we do not have to walk through all the elements (like we have to do in case of a SLL).

```
subalgorithm insertLast(dll, elem) is:
//pre: dll is a DLL, elem is TElem
//post: elem is added to the end of dll
   newNode ← allocate() //allocate a new DLLNode
   [newNode].info ← elem
   [newNode].next ← NIL
   [newNode].prev ← dll.tail
   if dll.head = NIL then //the list is empty
      dll.head ← newNode
      dll.tail ← newNode
   else
      [dll.tail].next ← newNode
      dll.tail ← newNode
   end-if
end-subalgorithm
```

- Complexity:

```
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   [newNode].info ← elem
   [newNode].next ← NIL
   [newNode].prev ← dll.tail
   if dll.head = NIL then //the list is empty
      dll.head ← newNode
      dll.tail ← newNode
   else
      [dll.tail].next ← newNode
      dll.tail ← newNode
   end-if
end-subalgorithm
```
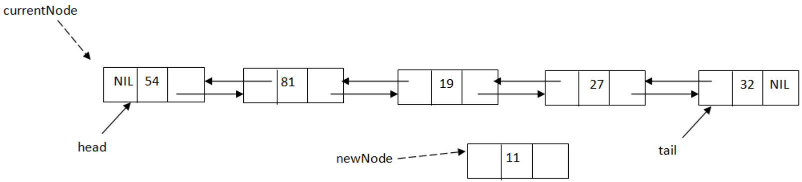

- Complexity: $\Theta(1)$

DLL - Insert on position

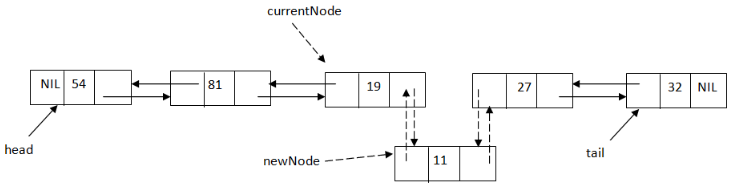
- The basic principle of inserting a new element at a given position is the same as in case of a SLL.
- The main difference is that we need to set more links (we have the *prev* links as well) and we have to check whether we modify the tail of the list.
- In case of a SLL we *had to* stop at the node after which we wanted to insert an element, in case of a DLL we can stop before or after the node (but we have to decide in advance, because this decision influences the special cases we need to test).

- Let's insert value 46 at the 4^{th} position in the following list:



DLL - Insert on position

- We move with the *currentNode* to position 3, and set the 4 links.



DLL - Insert at a position

```
subalgorithm insertPosition(dll, pos, elem) is:
//pre: dll is a DLL; pos is an integer number; elem is a TElem
//post: elem will be inserted on position pos in dll
   if pos < 1 then
      @ error, invalid position
   else if pos = 1 then
      insertFirst(dll, elem)
   else
      currentNode ← dll.head
      currentPos ← 1
      while currentNode ≠ NIL and currentPos < pos - 1 execute
         currentNode ← [currentNode].next
         currentPos ← currentPos + 1
      end-while
//continued on the next slide...
```

DLL - Insert at position

```
        if currentNode = NIL then
            @error, invalid position
        else if currentNode = dll.tail then
            insertLast(dll, elem)
        else
            newNode ← alocate()
            [newNode].info ← elem
            [newNode].next ← [currentNode].next
            [newNode].prev ← currentNode
            [[currentNode].next].prev ← newNode
            [currentNode].next ← newNode
        end-if
    end-if
end-subalgorithm
```

- Complexitate: $O(n)$

DLL - Insert at a position

- Observations regarding the *insertPosition* subalgorithm:
  - We did not implement the *insertFirst* subalgorithm, but we suppose it exists.
  - The order in which we set the links is important: reversing the setting of the last two links will lead to a problem with the list.
  - It is possible to use two *currentNodes*: after we found the node after which we insert a new element, we can do the following:

nodeAfter ← currentNode
nodeBefore ← [currentNode].next
//now we insert between nodeAfter and nodeBefore
[newNode].next ← nodeBefore
[newNode].prev ← nodeAfter
[nodeBefore].prev ← newNode
[nodeAfter].next ← newNode

DLL - Delete a given element

- If we want to delete a node with a given element, we first have to find the node:
  - we can use the *search* function (discussed at SLL, but it is the same here as well)
  - we can walk through the elements of the list until we find the node with the element (this is implemented below)

DLL - Delete a given element

```
function deleteElement(dll, elem) is:
//pre: dll is a DLL, elem is a TElem
//post: the node with element elem will be removed and returned
    currentNode ← dll.head
    while currentNode ≠ NIL and [currentNode].info ≠ elem execute
        currentNode ← [currentNode].next
    end-while
    deletedNode ← currentNode
    if currentNode ≠ NIL then
        if currentNode = dll.head then
            deleteElement ← deleteFirst(dll)
        else if currentNode = dll.tail then
            deleteElement ← deleteLast(dll)
        else
//continued on the next slide...
```

DLL - Delete a given element

```
        [[currentNode].next].prev ← [currentNode].prev
        [[currentNode].prev].next ← [currentNode].next
        @set links of deletedNode to NIL
      end-if
   end-if
   deleteElement ← deletedNode
end-function
```

- Complexity: $O(n)$
- If we used the *search* algorithm to find the node to delete, the complexity would still be $O(n)$ - *deleteElement* would be $\Theta(1)$, but searching is $O(n)$

DLL - Iterator

- The iterator for a DLL is identical to the iterator for the SLL (but *currentNode* is *DLLNode* not *SLLNode*).

Algorithmic problems using Linked Lists

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- Find the n^{th} node from the end of a SLL.
- Simple approach: go through all elements to count the length of the list. When we know the length, we know at which position the n^{th} node from the end is. Start again from the beginning and go to that position.
- Can we do it in one single pass over the list?

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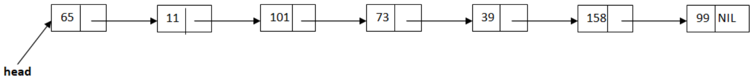
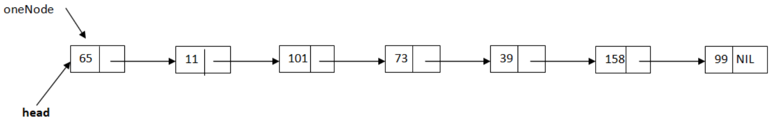
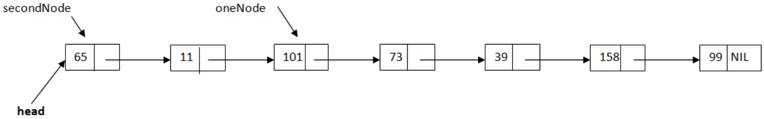
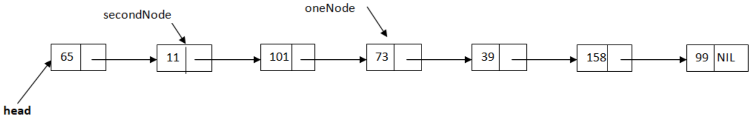
- Simple approach: go through all elements to count the length of the list. When we know the length, we know at which position the n^{th} node from the end is. Start again from the beginning and go to that position.
- Can we do it in one single pass over the list?
- We need to use two auxiliary variables, two nodes, both set to the first node of the list. At the beginning of the algorithm we will go forward $n-1$ times with one of the nodes. Once the first node is at the n^{th} position, we move with both nodes in parallel. When the first node gets to the end of the list, the second one is at the n^{th} element from the end of the list.

- We want to find the 3^{rd} node from the end (the one with information 39)




oneNode
65
11
101
73
39
158
99
NIL
head


secondNode
oneNode
65
11
101
73
39
158
99
NIL
head


secondNode
oneNode
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NIL
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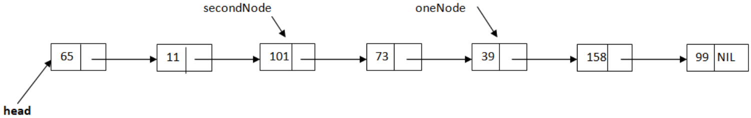
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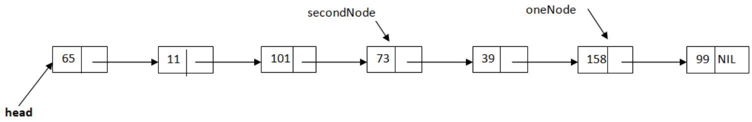
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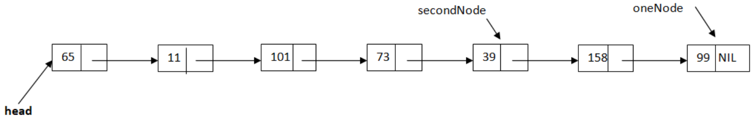
secondNode
oneNode
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73
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NIL
head

N-th node from the end of the list

function findNthFromEnd (sll, n) **is:**
//pre: sll is a SLL, n is an integer number
//post: the n-th node from the end of the list or NIL
  oneNode $\leftarrow$ sll.head
  secondNode $\leftarrow$ sll.head
  position $\leftarrow$ 1
  while position $<$ n **and** oneNode $\neq$ NIL **execute**
    oneNode $\leftarrow$ [oneNode].next
    position $\leftarrow$ position $+$ 1
  end-while
  if oneNode $=$ NIL **then**
    findNthFromEnd $\leftarrow$ NIL
  else
  //continued on the next slide...

N-th node from the end of the list

```
    while [oneNode].next ≠ NIL execute
        oneNode ← [oneNode].next
        secondNode ← [secondNode].next
    end-while
    findNthFromEnd ← secondNode
  end-if
end-function
```

- Is this approach really better than the simple one (does it make fewer steps)?

- Write a subalgorithm which rotates a singly linked list (moves the first element to become the last one).

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  - We have to do two things: remove the first node and then attach it after the last one.
  - Special cases:

- Write a subalgorithm which rotates a singly linked list (moves the first element to become the last one).
  - We have to do two things: remove the first node and then attach it after the last one.
  - Special cases:
    - an empty list
    - list with a single node

```
subalgorithm rotate(sll) is:
  if NOT (sll.head = NIL OR [sll.head].next = NIL) then
    first ← sll.head //save the first node
    sll.head ← [sll.head].next remove the first node
    current ← sll.head
    while [current].next ≠ NIL execute
      current ← [current].next
    end-while
    [current].next ← first
    [first].next ← NIL
    //make sure it does not point back to the new head node
  end-if
end-subalgorithm
```

- Complexity:

```
subalgorithm rotate(sll) is:
   if NOT (sll.head = NIL OR [sll.head].next = NIL) then
      first ← sll.head //save the first node
      sll.head ← [sll.head].next remove the first node
      current ← sll.head
      while [current].next ≠ NIL execute
         current ← [current].next
      end-while
      [current].next ← first
      [first].next ← NIL
      //make sure it does not point back to the new head node
   end-if
end-subalgorithm
```

- Complexity: $\Theta(n)$

Think about it

- Given the first node of a SLL, determine whether the list ends with a node that has NIL as *next* or whether it ends with a cycle (the *last* node contains the address of a previous node as *next*).
- If the list from the previous problems contains a cycle, find the length of the cycle.
- Find if a SLL has an even or an odd number of elements, without counting the number of nodes in any way.
- Reverse a SLL non-recursively in linear time using $\Theta(1)$ extra storage.

Sorted Lists

- A *sorted list* (or ordered list) is a list in which the elements from the nodes are in a specific order, given by a *relation*.
- This *relation* can be $<$, $\leq$, $>$ or $\geq$, but we can also work with an abstract relation.
- Using an abstract relation will give us more flexibility: we can easily change the relation (without changing the code written for the sorted list) and we can have, in the same application, lists with elements ordered by different relations.

The relation - recap

- You can imagine the *relation* as a function with two parameters (two *TComp* elems):

$$relation(c_1, c_2) = \begin{cases} true, & "c_1 \leq c_2" \\ false, & otherwise \end{cases}$$

- $"c_1 \leq c_2"$ means that c_1 should be in front of c_2 when ordering the elements.

- When we have a sorted list (or any sorted structure or container) we will keep the relation used for ordering the elements as part of the structure. We will have a field that represents this relation.

- In the following we will talk about a *sorted singly linked list* (representation and code for a *sorted doubly linked list* is really similar).

Sorted List - representation

- We need two structures: *Node - SSLLNode* and *Sorted Singly Linked List - SSLL*

<u>SSLLNode:</u>
  info: TComp
  next: $\uparrow$ SSLLNode

<u>SSLL:</u>
  head: $\uparrow$ SSLLNode
  rel: $\uparrow$ Relation

SSLL - Initialization

- The relation is passed as a parameter to the *init* function, the function which initializes a new SSLL.
- In this way, we can create multiple SSLLs with different relations.

subalgorithm init (ssll, rel) **is:**
//pre: rel is a relation
//post: ssll is an empty SSLL
    ssll.head ← NIL
    ssll.rel ← rel
end-subalgorithm

- Complexity: $\Theta(1)$

SSLL - Insert

- Since we have a singly-linked list we need to find the node *after* which we insert the new element (otherwise we cannot set the links correctly).
- The node we want to insert after is the first node whose successor is *greater than* the element we want to insert (where *greater than* is represented by the value *false* returned by the relation).
- We have two special cases:
  - an empty SSLL list
  - when we insert before the first node

SSLL - insert

```
subalgorithm insert (ssll, elem) is:
//pre: ssll is a SSLL; elem is a TComp
//post: the element elem was inserted into ssll to where it belongs
   newNode ← allocate()
   [newNode].info ← elem
   [newNode].next ← NIL
   if ssll.head = NIL then
   //the list is empty
      ssll.head ← newNode
   else if ssll.rel(elem, [ssll.head].info) then
   //elem is "less than" the info from the head
      [newNode].next ← ssll.head
      ssll.head ← newNode
   else
//continued on the next slide...
```

SSLL - insert

cn ← ssll.head *//cn - current node*
while [cn].next $\neq$ NIL **and** ssll.rel(elem, [[cn].next].info) = false **execute**
cn ← [cn].next
end-while
//now insert after cn
[newNode].next ← [cn].next
[cn].next ← newNode
end-if
end-subalgorithm

- Complexity:

SSLL - insert

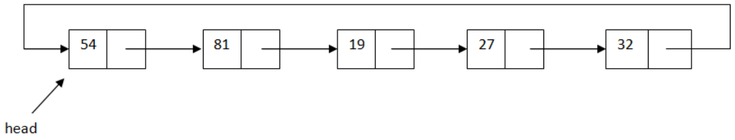
```
    cn ← ssll.head //cn - current node
    while [cn].next ≠ NIL and ssll.rel(elem, [[cn].next].info) = false execute
      cn ← [cn].next
    end-while
    //now insert after cn
    [newNode].next ← [cn].next
    [cn].next ← newNode
  end-if
end-subalgorithm
```

- Complexity: $O(n)$

SSLL - Other operations

- The search operation is identical to the search operation for a SLL (except that we can stop looking for the element when we get to the first element that is "greater than" the one we are looking for).
- The delete operations are identical to the same operations for a SLL.
- The return an element from a position operation is identical to the same operation for a SLL.
- The iterator for a SSLL is identical to the iterator to a SLL.

- 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)

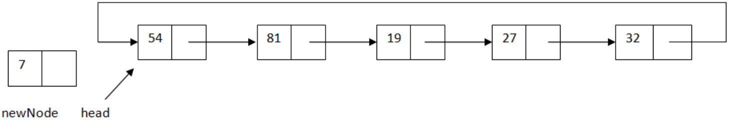
- Operations for a circular list have to consider the following two important aspects:
  - The *last* node of the list is the one whose *next* field is the *head* of the list.
  - Inserting before the head, or removing the head of the list, is no longer a simple $\Theta(1)$ complexity operation, because we have to change the *next* field of the last node as well (and for this we have to find the last node).
  - However, retaining the tail node as well, even in case of singly linked list, will help with these operations.

- 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*.

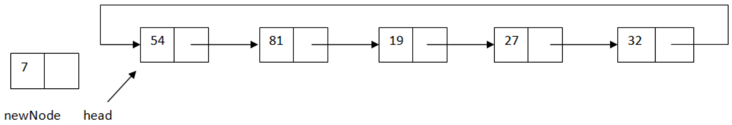
<u>CSLLNode:</u>
    info: TElem
    next: ↑ CSLLNode

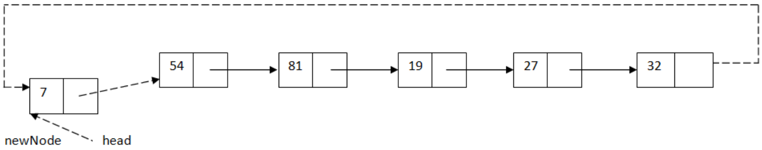
<u>CSLL:</u>
    head: ↑ CSLLNode

CSLL - InsertFirst



CSLL - InsertFirst





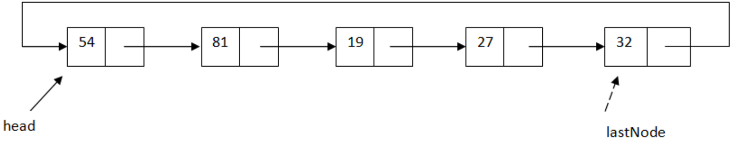
CSLL - InsertFirst

```
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...
```

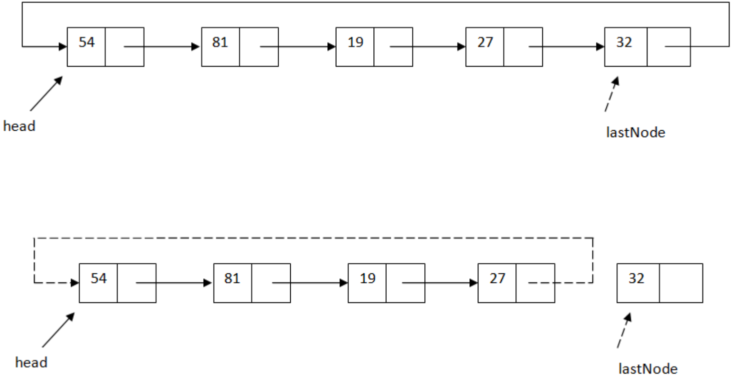
[newNode].next ← csll.head
[lastNode].next ← newNode
csll.head ← newNode
end-if
end-subalgorithm

- 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



```
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 and make invalid 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 after 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.

- 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.

- 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), otherwise we can keep iterating through 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.

- 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.

Summary

- Linked list variants:
  - Doubly linked list
  - Sorted list
  - Circular list
- Extra reading - A think about problem for which the solution will be in next week's extra reading.