

DS – Seminar 4

Sorted MultiMap (SMM)

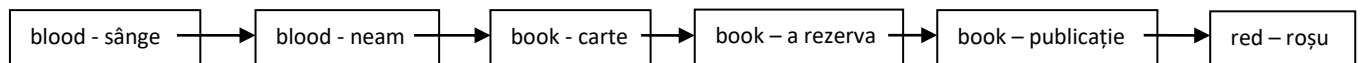
- Map – contains key-value pairs. Keys are unique, each key has a single associated value.
- MultiMap – a key can have multiple associated values (can be considered a list of values).
- Sorted MultiMap – there is a relation R defined on the keys and they are ordered based on the keys. There is no particular order of the values belonging to a key (we do not order based on the values)

Problem: Implement the SortedMultiMap ADT – use a singly linked representation with dynamic allocation

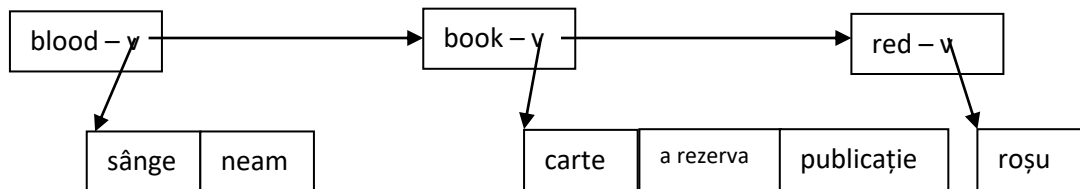
Ex. a multimap with the translation of different English words in Romanian

- book – carte, a rezerva, publicație
- red – roșu
- blood – sânge, neam

Representation 1: Singly linked list of <key, value> pairs. There might be multiple nodes with the same key, they will be placed one after the other (since the nodes are sorted based on the keys).



Representation 2: Singly linked list of <key, list of values> pairs. The keys are unique and sorted.



No matter which representation we choose, the content of the SMM is the same: we have 6 key-value pairs.

How could we represent the *list of values* from the second representation?

- Data structure level:
 - o Dynamic array, SLL, DLL
- ADT level:
 - o List, Bag

We will consider that the *list of values* is actually an ADT List, already implemented (together with the ListIterator)

TElem:

k: TKey

vl: List

Node:

info: TElem

next: ↑Node

SMM:

head: ↑Node

R: Relation

$$R(k_1, k_2) = \begin{cases} \text{true, if } "k_1 \leq k_2" \text{ (} k_1 \text{ comes before } k_2 \text{)} \\ \text{false, otherwise} \end{cases}$$

Iterator:

We need to keep in the iterator:

- the SMM
- a reference to the current node from the SMM
- an iterator for the list of values associated to the current node

Obs 1: In a SMM we have key-value pairs, so current element from the iterator has to be a key-value pair. Even if we chose representation 2, we cannot say that our current element is a key and a list of values.

Obs 2: Instead of an iterator over the list of values associated to the current node we could have used the index/position of the current element from the list of values (since it is a list and it has positions). But, working with an iterator over the value list is more efficient.

IteratorSMM:

smm: SMM

current: ↑Node

itL: IteratorList

Iterator operations: init, valid, next, getCurrent (returns a <key, value> pair).

Printing the elements of a SMM using the iterator:

```
Subalgorithm print(smm) is:
  iterator(smm, it)
  while valid(it) execute:
    getCurrent(it, <k,v>)
    @print k and v
    next(it)
  end-while
end-subalgorithm
```

The print subalgorithm looks in the same way independently of the representation of the iterator and the representation of the map!

Operations for the iterator

subalgorithm init (it, smm) is:

```

        it.smm ← smm
        it.current ← smm.head
        if it.current ≠ NIL then:
            iterator([it.smm.head].info.vl, it.itL)
        end-if
    end-subalgorithm
Complexity:  $\Theta(1)$ 

subalgorithm getCurrent(it) is: // result will be a <k, v> pair
    if it.current = NIL then
        @throw exception
    end-if
    k ← [it.current].info.k
    v ← getCurrent(it.itL)
    getCurrent ← <k,v>
end-subalgorithm
Complexity:  $\Theta(1)$ 

function valid(it):
    if it.current ≠ NIL then
        valid ← true
    else
        valid ← false
    end-function
Complexity:  $\Theta(1)$ 

subalgorithm next(it) is:
    if it.current = NIL then
        @throw exception
    end-if
    next(it.itL)
    if not valid(it.itL) then
        it.current ← [it.current].next
        if it.current ≠ NIL then
            iterator ([it.current].info.vl, it.itL)
        end-if
    end-if
end-subalgorithm
Complexity:  $\Theta(1)$ 

subalgorithm first(it) is:
    it.current ← it.smm.head
    if it.current ≠ NIL then:
        iterator([it.smm.head].info.vl, it.itL)
    end-if
end-subalgorithm
Complexity:  $\Theta(1)$ 

```

Operations for the sorted multi map

Notations for the complexities:

n – number of distinct keys

smm – total number of elements

subalgorithm init(smm, R) **is:**

 smm.R \leftarrow R

 smm.head \leftarrow NIL

end-subalgorithm

Complexity: $\theta(1)$

subalgorithm destroy(smm) **is:**

while smm.head \neq NIL **execute:**

 aux \leftarrow smm.head

 smm.head \leftarrow [smm.head].next

 destroy([aux].info.v1)

 free(aux)

end-while

end-subalgorithm

Complexity:

If destroy for list is $\theta(1) \Rightarrow \theta(n)$

If destroy for list is $\theta(\text{length of list}) \Rightarrow \theta(\text{smm})$

//auxiliary function that will help us with the other operations (*private* function, it is not part of the interface).

//pre: smm is SMM, k is a Tkey

//post: kNode is a \uparrow Node, prevNode is a \uparrow Node. If there is a node with k as key, kNode will be that node and prevNode will be the previous node. If there is no node with k as key, kNode will be NIL and prevNode will be the node after which the key k should be.

For the previous example (the one with the words and translations):

searchNode for „book” -> kNode the node with book, prevNode the node with blood

searchNode for „blood” -> kNode the node with blood, prevNode will be NIL

searchNode for „day” -> kNode will be NIL, prevNode the node with book

searchNode for „air” -> kNode will be NIL, prevNode will be NIL

subalgorithm searchNode(smm, k, kNode, prevNode) **is:**

 aux \leftarrow smm.head

 prev \leftarrow NIL

 found \leftarrow false

while aux \neq NIL **and** smm.R([aux].info.k, k) **and not found execute**

if [aux].info.k = k **then**

 found \leftarrow true

else

 prev \leftarrow aux

 aux \leftarrow [aux].next

end-if

end-while

if found **then**

 kNode \leftarrow aux

 prevNode \leftarrow prev

else

 kNode \leftarrow NIL

```

        prevNode ← prev
    end-if
end-subalgorithm

```

Complexity: $O(n)$

```

subalgorithm search(smm, k, list) is:
    searchNode (smm, k, kNode, prevNode)
    if kNode = NIL then
        init(list) // return an empty list
    else
        list ← [aux].info.vl
    end-if
end-subalgorithm

```

Complexity: $O(n)$

```

subalgorithm add(smm, k, v) is:
    searchNode(smm, k, kNode, prevNode)
    if kNode = NIL then
        addANewKey (smm, k, v, prevNode)
    else
        addEnd([kNode].info.vl, v)
    end-if
end-subalgorithm

```

Complexity:

//searchNode is $O(n)$
 //addANewKey is $\Theta(1)$ operation (we will use the prevNode)
 //instead of addEnd another add function can be used (so it can have $\Theta(1)$ complexity)
 If addEnd (or whatever function is used for values) is $\Theta(1) \Rightarrow O(n)$
 If addEnd (or whatever function is used for values) is $\Theta(\text{length of the list}) \Rightarrow O(smm)$

//auxiliary operation (not part of interface)
 //pre: smm is a SMM, k is a TKey, v is a TElem/ TValue, prevNode is a ↑Node (the node after which the new node should be added)
 //post: a new node with key k and value v is added to the smm. The order of the keys will respect the relation.

```

subalgorithm addANewKey (smm, k, v, prevNode) is:
    allocate(newNode)
    [newNode].info.k ← k
    init ([newNode].info.vl)
    addEnd([newNode].info.vl, v)
    if prevNode = NIL then
        [newNode].next ← smm.head
        smm.head ← newNode
    else
        [newNode].next ← [prevNode].next
        [prevNode].next ← newNode
    end-if
end-subalgorithm

```

Complexity: $\Theta(1)$ //supposing addToEnd is $\Theta(1)$ - which is true since in this situation we will always add an element into an empty list

```

function remove(smm, k, v) is:

```

```

searchNode(smm, k, kNode, prevNode)
if kNode  $\neq$  NIL then
    pos  $\leftarrow$  indexOf([kNode].info.v1, v)
    if pos  $\neq$  -1 then
        remove([kNode].info.v1, pos, e)
    end-if
    if isEmpty([kNode].info.v1) then
        removeKey(smm, k, prevNode)
    end-if
    remove  $\leftarrow$  true
end-if
remove  $\leftarrow$  false
end-subalgorithm
Complexity:  $O(\text{smm})$ 

```

```

//auxiliary operation (not part of the interface)
//pre: smm is a SMM, k is a TKey, prevNode is a ↑Node, smm contains a node with key k
after the node prevNode (if prevNode is NIL, then the first node if smm contains the
key k). The value list of the node with key k is empty.
//post: the node containing key k is removed from smm
subalgorithm removeKey(smm, k, prevNode) is:
    if prevNode = NIL then
        deleted ← smm.head
        smm.head ← [smm.head].next
        destroy([deleted].info.vl)
        free(deleted)
    else
        deleted ← [prevNode].next
        [prevNode].next ← [[prevNode].next].next
        destroy([deleted].info.vl)
        free(deleted)
    end-if
end-subalgorithm
Complexity:  $\Theta(1)$ 
Destroy will destroy an empty list  $\Rightarrow \Theta(1)$ 

```