COMP250: Dictionary ADT & Binary Search Trees

Lecture 21
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Dictionary ADT

• A dictionary (a.k.a. map) stores a set of pairs (key, value)
  – (word, definition)
  – (studentID, studentRecord)
  – (flightNumber, flightInformation)
• Data is accessed only through key:
  – Object find(key k)
  – void insert(key k, Object v)
  – Object remove(key k)
• If the keys can be ordered
  – Object previous(key k)
  – Object next(key k)
Dictionary vehicle = {
    'car':'a road vehicle, typically with four wheels, powered by an internal combustion engine and able to carry a small number of people.';
    'bicyle':'a vehicle composed of two wheels held in a frame one behind the other, propelled by pedals and steered with handlebars attached to the front wheel.'
}
## Array implementation

<table>
<thead>
<tr>
<th>Key</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key 1</td>
<td>Content 1</td>
</tr>
<tr>
<td>Key 2</td>
<td>Content 2</td>
</tr>
<tr>
<td>Key 3</td>
<td>Content 3</td>
</tr>
<tr>
<td>Key 4</td>
<td>Content 4</td>
</tr>
<tr>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
</tr>
</tbody>
</table>

Size = 4
Array implementation

Array of pairs (key, value)

- **find**(key k) : scan array to find key \(O(n)\)
- **insert**(key k, Object v):
  - Add the pair (k, v) at the end of the array \(O(1)\)
  - Increase size by one
- **remove**(key k) \(O(n)\)
  - Scan array to find k
  - Shift left remaining elements
Array implementation

Remove('Key 2')

<table>
<thead>
<tr>
<th>Key</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key 1</td>
<td>Content 1</td>
</tr>
<tr>
<td>Key 2</td>
<td>Content 2</td>
</tr>
<tr>
<td>Key 3</td>
<td>Content 3</td>
</tr>
<tr>
<td>Key 4</td>
<td>Content 4</td>
</tr>
<tr>
<td>∅</td>
<td>∅</td>
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</tbody>
</table>
## Sorted Array implementation

<table>
<thead>
<tr>
<th>Key</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
</tr>
<tr>
<td>8</td>
<td>x</td>
</tr>
<tr>
<td>12</td>
<td>x</td>
</tr>
<tr>
<td>15</td>
<td>x</td>
</tr>
<tr>
<td>16</td>
<td>x</td>
</tr>
<tr>
<td>21</td>
<td>x</td>
</tr>
<tr>
<td>33</td>
<td>x</td>
</tr>
<tr>
<td>42</td>
<td>x</td>
</tr>
<tr>
<td>53</td>
<td>x</td>
</tr>
<tr>
<td>55</td>
<td>x</td>
</tr>
<tr>
<td>62</td>
<td>x</td>
</tr>
</tbody>
</table>
Sorted array implementation

Array of pairs (key, value), sorted by key

- find(key k) : binary search to find key \( O(\log n) \)
- insert(key k, Object v):
  - Binary search to find where to insert, \( O(\log n) \)
  - Shift element right to insert new element, \( O(n) \)
- remove(key k)
  - Binary search to find key, \( O(\log n) \)
  - Shift left remaining elements, \( O(n) \)
Remove in a sorted Array

Remove('12')

<table>
<thead>
<tr>
<th>Key</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>x</td>
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<tr>
<td>8</td>
<td>x</td>
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<tr>
<td>12</td>
<td>x</td>
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<tr>
<td>15</td>
<td>x</td>
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<tr>
<td>16</td>
<td>x</td>
</tr>
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<td>21</td>
<td>x</td>
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<td>33</td>
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</tr>
<tr>
<td>55</td>
<td>x</td>
</tr>
<tr>
<td>62</td>
<td>x</td>
</tr>
</tbody>
</table>

Find: $O(\log n)$

Remove: $O(n)$
Linked-list implementation
Linked-list implementation

Linked-list where each node contain a pair (key, value)

- **find**(key k) : scan list to find key \(O(n)\)
- **insert**(key k, Object v): \(O(1)\)
  - Add the pair \((k, v)\) at the end of the list
- **remove**(key k) \(O(n)\)
  - Scan list to find k, \(O(n)\)
  - Remove node, \(O(1)\)

Note: Keeping the linked-list sorted does not help, as binary search can’t be done in time \(O(\log n)\) in linked lists. Why?
## Implementations of dictionary

<table>
<thead>
<tr>
<th>Method</th>
<th>find</th>
<th>insert</th>
<th>remove</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array</td>
<td>$O(n)$</td>
<td>$O(1)$</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>Linked-list</td>
<td>$O(n)$</td>
<td>$O(1)$</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>Sorted array</td>
<td>$O(\log n)$</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
</tr>
</tbody>
</table>
A **binary search tree** (BST) is a binary tree such that for any node $n$,

- The elements of the left subtree of $n$ have values smaller or equal to $n$
- The elements of the right subtree of $n$ have values larger or equal to $n$

(In the figure, we show only the keys)
find(‘8’)
BST - Find

Idea: 1) Start from the root of the tree
     2) Choose if you should go to the left or right child.
     3) Repeat until you find the key sought or get to a leaf.

Algorithm find(node n, key k)

Input: The node n at the root of the tree to explore.
       The key k to find

Output: Returns one node with key equal to k

if (n = null) then return null
if (n.key = k) then return n
if (n.key > k) then return find(n.leftChild, k)
if (n.key < k) then return find(n.rightChild, k)

Can you write a non-recursive version of this algorithm?
insert('2')
BST - insert

Idea: 1) Find the leaf where the insertion will take place, by going down the tree as for the “find” algo.
   2) Add a new left or right child to that leaf

Algorithm insert(node n, key k, object v)
Input: The key k and information i to be added to the subtree rooted at n. Assumes n!= null
Output: Inserts a new node (k,i) in the subtree rooted at n

if (k ≤ n.key) then
   if (n.leftChild != null) then
      insert(n.leftChild, k, v)
   else n.setLeftChild( new node(k,v) );
else
   if (n.rightChild != null) then
      insert(n.rightChild, k, v)
   else n.setRightChild( new node(k,v) );
BST - remove

Idea: 1) Find the node N to be removed using the “find” algo
2) - If N is a leaf, simply remove it
    - If N is an internal node with only one child, replace N by its child
    - If N is an internal node with two children, N will be replaced by the node N’ that has the next key largest key after N.
To find N’:
    i) Follow the right child of N and then go down left children until no left child is found.
       The node found is N’
    Overwrite N by N’.
remove('6')
remove('8')
remove('3')
Implementation

// A small utility function
Algorithm replace(node x, node y)
Input: Two nodes x and y
Output: Copies node y onto node x, overwriting x.
if (x.parent != null)
    if (x.parent.leftChild = x) then
        x.parent.setLeftChild(y)
    else x.parent.setRightChild(y)
if (y != null) then y.parent ← x.parent
Algorithm remove(node root, key k)

Input: The key k of the node to be removed from the subtree rooted at n

Output: Removes node with key k and returns it.

node x ← find(root, k)

if (x=null) then return null // key k was not found

if ( x.isALeaf() ) then replace(x, null); return

if (x.leftChild = null or x.rightChild = null) then // x has only one child

if ( x.leftChild = null ) then
    replace(x, x.rightChild) // x was right child
else if ( x.rightChild = null )
    replace(x, x.leftChild) // x was left child

else // x has two children, find successor of x
    suc ← x.rightChild

while (suc.leftChild != null) do
    suc ← suc.leftChild
    x.value = suc.value
    x.key = suc.key
    replace(suc, suc.rightChild)