

# Hogebomen

Lisette de Schipper (s1396250) en Micky Faas (s1407937)

## Abstract

Blablabla

## 1 Inleiding

AVL-bomen, splay-bomen en treaps zijn klassieke datastructuren die ingezet worden om een verzameling gegevens te faciliteren. Het zijn zelfbalancerende binaire zoekbomen die elk een vorm van ruimte en/of tijd-efficiëntie aanbieden. Er worden experimenten verricht om de prestatie van deze zelf-balancerende zoekbomen te vergelijken aan de hand van ophaaltijd van data, mate van herstructurering en het verwijderen van knopen. Ook wordt de prestatie van deze zoekbomen uitgezet tegen de ongebalanceerde tegenhanger, de binaire zoekboom.

## 2 Werkwijze

De vier bomen zijn conceptueel eenvoudig en relatief makkelijk te implementeren. Voor alle vier de bomen wordt dezelfde zoekmethode gebruikt. Deze is in het slechtste geval  $O(\log n)$ .

### 2.1 Implementatie binaire zoekboom

De binaire zoekboom (BST) vormt de basis voor alle zogeheten *zelf-organiserende bomen*, zoals de AVL- of SplayTree. Aan de grondslag van de BST ligt de *binaire-zoekboom-eigenschap*, die zorgt dat de boom op de “gretige” manier kan worden doorzocht in plaats van een *exhaustive search*. Hierdoor is het mogelijk om een knoop in hooguit  $O(\log(n))$  stappen te vinden. Kort samengevat houdt de bst-eigenschap het volgende in:

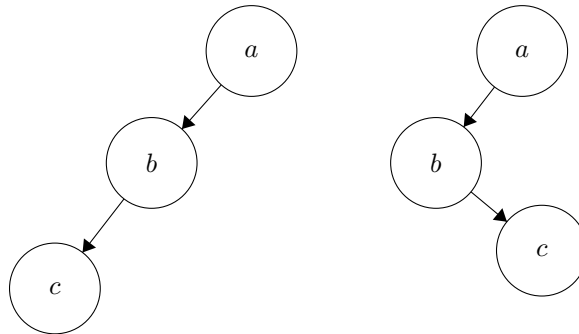
- Linker-kindknopen hebben altijd een kleinere waarde dan hun ouder, rechter-kindknopen altijd een grotere.
- Bij een MIN-boom is dit omgekeerd. Onze implementatie is enkel een MAX-boom.
- Toevoegen kan zonder verwisselen worden uitgevoerd (in tegenstelling tot bijv. een heap).
- Voor verwijderen of vervangen moet afhankelijk van de plaats van de knoop wel worden verwisseld.

*Nu ben ik moe*

## 2.2 Implementatie AVL-bomen

Knopen van een AVL-boom hebben een *balansfactor*, die altijd -1, 0 of 1 moet zijn. In deze implementatie is de balansfactor de hoogte van de rechtersubboom min de hoogte van de linkersubboom. Dit houdt dus in dat de hoogte van de linkersubboom van de wortel met maar 1 knoop kan verschillen van de hoogte van de rechtersubboom van de wortel. Het moment dat de balansfactor van een knoop minder dan -1 of meer dan 1 wordt, moet de boom geherstructureerd worden, om deze eigenschap te herstellen.

Om de balansfactor voor elke knoop te berekenen, houdt elke knoop zijn eigen hoogte bij. De balansfactor van een knoop wordt hersteld door rotaties. De richting en de hoeveelheid van de rotaties hangt af van de vorm van de betreffende (sub)boom. De volgende twee vormen en hun spiegelbeelden kunnen voorkomen bij het verwijderen of toevoegen van een knoop:



In het eerste geval moet de wortel naar rechts worden geroteerd. In het tweede geval moeten we eerst naar de staat van de eerste subboom komen, door b naar links te roteren. Voor de spiegelbeelden van deze twee vormen geldt hetzelfde alleen in spiegelbeeld.

In deze implementatie van een AVL-boom bedraagt het toevoegen van een knoop in het ergste geval  $O(\log n)$  tijd, waarbij  $n$  staat voor de hoogte van de boom. Eerst moet er gekeken worden of de data niet al in de boom voorkomt ( $O(\log n)$ ) en vervolgens moet de boom op basis van de toevoeging geherstructureerd worden. Dit laatste is in het ergste geval  $O(\log n)$ , omdat dan de gehele boom tot de wortel moeten worden nagelopen.

De complexiteitsgraad van het verwijderen van een knoop is gelijk aan die van het toevoegen van een knoop. In deze implementatie zoeken we in de rechtersubboom het kleinste kind en vervangen we de te verwijderen knoop met deze knoop. Dit heeft een duur van  $O(\log n)$ . Als hij geen rechtersubboom heeft, wordt de node weggegooid en wordt zijn linkersubboom de nieuwe boom.

## 2.3 Implementatie Splay-bomen

TO DO

## 2.4 Implementatie Treaps

Treap lijkt in veel opzichten op een AVL-boom. De balansfactor per knoop heeft echter plaats gemaakt voor een prioriteit per knoop. Deze prioriteit wordt bij het toevoegen van een knoop willekeurig bepaald. De complexiteit voor het toevoegen en verwijderen van een knoop is hetzelfde als bij de AVL-boom.

Bij het toevoegen van een knoop moet er nog steeds omhoog gelopen worden in de boom, totdat de prioriteit van de toegevoegde knoop kleiner is dan de prioriteit van de ouder. Als dit niet het geval is, blijft de toegevoegde knoop omhoog roteren. In het ergste geval kan het dus weer zo zijn dat we tot de wortel door moeten blijven lopen.

Bij het verwijderen van een knoop blijven we de betreffende knoop roteren naar het kind met de grootste prioriteit. Uiteindelijk belanden we dan in de situatie dat de knoop maar een of geen kinderen heeft. In het eerste geval verwijderen we de knoop en plakken zijn subboom terug aan de boom op zijn plek en in het tweede geval verwijderen we de knoop. In het slechtste geval duurt dit dus ook  $O(\log n)$  tijd.

## 3 Onderzoek

Een praktisch voorbeeld van binair zoeken in een grote boom is de spellingscontrole. Een spellingscontrole moet zeer snel voor een groot aantal strings kunnen bepalen of deze wel of niet tot de taal behoren. Aangezien er honderduizenden woorden in een taal zitten, is lineair zoeken geen optie. Voor onze experimenten hebben wij dit als uitgangspunt genomen en hieronder zullen we kort de experimenten toelichten die wij hebben uitgevoerd. In het volgende hoofdstuk staan vervolgens de resultaten beschreven.

### 3.1 Hooiberg

“Hooiberg” is de naam van het testprogramma dat we hebben geschreven speciaal ten behoeven van onze experimenten. Het is een klein console programma dat woorden uit een bestand omzet tot een boom in het geheugen. Deze boom kan vervolgens worden doorzocht met de input uit een ander bestand: de “naalden”. De syntax is als volgt:

```
hooiberg type hooiberg.txt naalden.txt [treap-random-range]
```

Hierbij is **type** één van **bst**, **avl**, **splay**, **treap**, het eerste bestand bevat de invoer voor de boom, het tweede bestand een verzameling strings als zoekopdracht en de vierde parameters is voorbehouden voor het type **treap**. De bestanden kunnen woorden of zinnen bevatten, gescheiden door regeleinden. De binaire bomen gebruiken lexicografische sortering die wordt geleverd door de operatoren **<** en **>** van de klasse **std::string**. Tijdens het zoeken wordt een exacte match gebruikt (case-sensitive, non-locale-aware).

## 3.2 Onderzoeks(deel)vragen

Met onze experimenten hebben we gepoogd een aantal eenvoudige vragen te beantwoorden over het gebruik van de verschillende binaire en zelf-organiserende bomen, te weten:

- Hoeveel meer rekenkracht kost het om grote datasets in te voegen in zelf-organiserende bomen tov binaire bomen?
- Levert een zelf-organiserende boom betere zoekprestaties en onder welke omstandigheden?
- Hoeveel extra geheugen kost een SOT?
- Wat is de invloed van de random-factor bij de Treap?

## 3.3 Meetmethoden

Om de bovenstaande vragen te toetsen, hebben we een aantal meetmethoden bedacht.

- Rekenkracht hebben we gemeten in milliseconden tussen aanvang en termineren van een berekening. We hebben de delta's berekend rond de relevante code blokken dmv de C++11 `chrono` klassen in de Standard Template Library. Alle test zijn volledig sequentieel en single-threaded uitgevoerd. Deze resultaten zijn representatie voor één bepaald systeem, vandaar dat we aantal % 'meer rekenkracht' als eenheid gebruiken.
- Zoekprestatie hebben we zowel met rekenkracht als zoekdiepte gemeten. De zoekdiepte is het aantal stappen dat vanaf de wortel moet worden gemaakt om bij de gewenste knoop te komen. We hebben hierbij naar het totaal aantal stappen gekeken en naar de gemiddelde zoekdiepte.
- Geheugen hebben we gemeten met de `valgrind` memory profiler. Dit programma wordt gebruikt voor het opsporen van geheugen lekken en houdt het aantal allocaties op de heap bij. Dit is representatie voor het aantal gealloceerde nodes. Aangezien hooiberg nauwelijks een eigen geheugen-voetafdruk heeft, zijn deze waarden representatief.

## 3.4 Input data

Voor ons experiment hebben we een taalbestand gebruikt van OpenTaal.org met meer dan 164.000 woorden. Dit is een relatief klein taalbestand, maar voldoende om verschillen te kunnen zien. We hebben een aantal testcondities gebruikt:

- Voor het inladen een wel of niet alfabetisch gesoorterd taalbestand gebruiken.
- Als zoekdocument hebben we een gedicht met 62 woorden gebruikt. Er zitten een aantal dubbele woorden in alsook een aantal woorden die niet in de woordenlijst voorkomen (werkwoordsvervoegingen).
- We hebben ook een conditie waarbij we alle woorden gezocht hebben, zowel in dezelfde, als in een andere volgorde dan dat ze zijn ingevoerd.

- We hebben één conditie waarbij we de random-range van de Treap hebben gevarieerd.

### 3.5 Hypothesen

- De binary search tree zal vermoedelijk het snelst nieuwe data toevoegen. De splay tree heeft veel ingewikkelde rotatie bij een insert, dus deze zal het traagst zijn.
- Bij het gedicht zal de splay boom waarschijnlijk het snelst zijn omdat deze optimaliseert voor herhalingen.
- ...
- De bomen die een aparte node-klasse gebruiken (avl en treap) gebruiken het meeste geheugen.
- De meest efficiënte randomfactor is afhankelijk van de grootte van de boom die geïmplementeerd gaat worden. Bij een kleine boom volstaat een kleine randomfactor, bij een grote boom volstaat een grote randomfactor.

## 4 Resultaten

### 4.1 Experiment 1

Hoeveel meer rekenkracht kost het om grote datasets in te voegen in zelf-organiserende bomen tov binaire bomen?

### 4.2 Experiment 2

Levert een zelf-organiserende boom betere zoekprestaties en onder welke omstandigheden?

### 4.3 Experiment 3

Hoeveel extra geheugen kost een SOT?

### 4.4 Experiment 4

Wat is de invloed van de random-factor bij de Treap?

## 5 Conclusies

## 6 Appendix

### 6.1 main.cc

```

1  /**
2   * main.cc:
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file main.cc
7   * @date 26-10-2014
8   */
9
10 #include <iostream>
11 #include "BinarySearchTree.h"
12 #include "Tree.h"
13 #include "AVLTree.h"
14 #include "SplayTree.h"
15 #include "Treap.h"
16 #include <string>
17
18 using namespace std;
19
20 // Makkelijk voor debuggen, moet nog beter
21 template<class T> void printTree( Tree<T> tree, int rows ) {
22     typename Tree<T>::odelist list = tree.row( 0 );
23     int row = 0;
24     while( !list.empty( ) && row < rows ) {
25         string offset;
26         for( int i = 0; i < ( 1 << (rows - row) ) - 1 ; ++i )
27             offset += ' ';
28
29
30         for( auto it = list.begin( ); it != list.end( ); ++it ) {
31             if( *it )
32                 cout << offset << (*it)->info() << " " << offset;
33             else
34                 cout << offset << ". " << offset;
35         }
36         cout << endl;
37         row++;
38         list = tree.row( row );
39     }
40 }
41
42 int main ( int argc, char **argv ) {
43
44     /* BST hieronder */
45
46     cout << "BST:" << endl;
47     BinarySearchTree<int> bst;
48
49     /* auto root = bst.pushBack( 10 );
50     bst.pushBack( 5 );
51     bst.pushBack( 15 );
52
53     bst.pushBack( 25 );
54     bst.pushBack( 1 );

```

```

55     bst.pushBack( -1 );
56     bst.pushBack( 11 );
57     bst.pushBack( 12 );*/
58
59     Tree<int>* bstP =&bst; // Dit werkt gewoon :-)
60
61     auto root =bstP->pushBack( 10 );
62     bstP->pushBack( 5 );
63     bstP->pushBack( 15 );
64
65     bstP->pushBack( 25 );
66     bstP->pushBack( 1 );
67     bstP->pushBack( -1 );
68     bstP->pushBack( 11 );
69     bstP->pushBack( 12 );
70
71     //printTree<int>( bst, 5 );
72
73
74     //bst.remove( bst.find( 0, 15 ) );
75     //bst.replace( -2, bst.find( 0, 5 ) );
76
77
78     printTree<int>( bst, 5 );
79
80     bst.remove( root );
81
82
83     printTree<int>( bst, 5 );
84
85     /* Splay Trees hieronder */
86
87     cout << "Splay Boom:" << endl;
88     SplayTree<int> splay;
89
90     splay.pushBack( 10 );
91     auto a =splay.pushBack( 5 );
92     splay.pushBack( 15 );
93
94     splay.pushBack( 25 );
95     auto b =splay.pushBack( 1 );
96     splay.pushBack( -1 );
97     auto c =splay.pushBack( 11 );
98     splay.pushBack( 12 );
99
100    //printTree<int>( splay, 5 );
101
102    //a->swapWith( b );
103    //splay.remove( splay.find( 0, 15 ) );
104    //splay.replace( -2, splay.find( 0, 5 ) );
105
106
107    printTree<int>( splay, 5 );
108

```

```

109     //splay.remove( root );
110
111     splay.splay( c );
112
113     printTree<int>( splay, 5 );
114
115     // Test AVLTree //
116
117     AVLTree<char> test;
118     test.insert( 'a' );
119     auto d = test.insert( 'b' );
120     test.insert( 'c' );
121     test.insert( 'd' );
122     test.insert( 'e' );
123     test.insert( 'f' );
124     test.insert( 'g' );
125     cout << "AVL Boompje:" << endl;
126     printTree<char>( test, 5 );
127     cout << d->info( ) << " verwijderen: " << endl;
128     test.remove( d );
129     printTree<char>( test, 5 );
130
131     // Test Treap //
132
133     cout << "Treap" << endl;
134
135     Treap<int> testTreap(5);
136     testTreap.insert(2);
137     testTreap.insert(3);
138     auto e = testTreap.insert(4);
139     testTreap.insert(5);
140     printTree<int>( testTreap, 5 );
141     testTreap.remove(e);
142     printTree<int>( testTreap, 5 );
143
144     return 0;
145 }

```

## 6.2 hooiberg.cc

```

1  /**
2   * hooiberg.cc:
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file helehogebomen.cc
7   * @date 10-12-2014
8   */
9
10 #include "BinarySearchTree.h"
11 #include "Tree.h"
12 #include "AVLTree.h"
13 #include "SplayTree.h"
14 #include "Treap.h"

```



```

15
16 #include <iostream>
17 #include <string>
18 #include <fstream>
19 #include <vector>
20 #include <chrono>
21
22 // Only works on *nix operating systems
23 // Needed for precision timing
24 #include <sys/time.h>
25
26 using namespace std;
27
28 // Makkelijk voor debuggen, moet nog beter
29 template<class T> void printTree( Tree<T> tree, int rows ) {
30     typename Tree<T>::nodelist list =tree.row( 0 );
31     int row =0;
32     while( !list.empty( ) && row < rows ) {
33         string offset;
34         for( int i =0; i < ( 1 << (rows - row) ) - 1 ; ++i )
35             offset += ' ';
36
37
38         for( auto it =list.begin( ); it != list.end( ); ++it ) {
39             if( *it )
40                 cout << offset << (*it)->info() << " " << offset;
41             else
42                 cout << offset << ". " << offset;
43         }
44         cout << endl;
45         row++;
46         list =tree.row( row );
47     }
48 }
49
50 int printUsage( const char* prog ) {
51
52     std::cout << "Reads an input file and searches it for a set of strings\n\n"
53         << "Usage: " << prog << " [type] [haystack] [needles]\n"
54         << "\t[type]\t\tTree type to use. One of 'splay', 'avl', 'treap', 'bst'\n"
55         << "\t[haystack]\tInput file, delimited by newlines\n"
56         << "\t[needles]\tFile containing sets of strings to search for, delimited by\n"
57         << "\t[random]\tOptimal customization of Treap\n"
58         << std::endl;
59     return 0;
60 }
61
62 bool extractNeedles( std::vector<string> &list, std::ifstream &file ) {
63     string needle;
64     while( !file.eof( ) ) {
65         std::getline( file, needle );
66         if( needle.size( ) )
67             list.push_back( needle );
68     }

```

```

69     return true;
70 }
71
72 bool fillTree( BinarySearchTree<string>* tree, std::ifstream &file ) {
73     string word;
74     while( !file.eof( ) ) {
75         std::getline( file, word );
76         if( word.size( ) )
77             tree->pushBack( word );
78     }
79     return true;
80 }
81
82 void findAll( std::vector<string> &list, BinarySearchTree<string>* tree ) {
83     int steps =0, found =0, notfound =0;
84     for( auto needle : list ) {
85         if( tree->find( 0, needle ) ) {
86             found++;
87             steps +=tree->lastSearchStepCount( );
88             if( found < 51 )
89                 std::cout << "Found " << needle << '\n'
90                 << " in " << tree->lastSearchStepCount( ) << " steps." << std::endl;
91         }
92         else if( ++notfound < 51 )
93             std::cout << "Didn't find " << needle << '\n' << std::endl;
94     }
95     if( found > 50 )
96         std::cout << found - 50 << " more results not shown here." << std::endl;
97     if( found )
98         cout << "Total search depth:          " << steps << endl
99         << "Number of matches:          " << found << endl
100         << "Number of misses:          " << notfound << endl
101         << "Average search depth (hits): " << steps/found << endl;
102 }
103
104 int main ( int argc, char **argv ) {
105
106     enum MODE { NONE =0, BST, AVL, SPLAY, TREAP };
107     int mode =NONE;
108
109     if( argc < 4 )
110         return printUsage( argv[0] );
111
112     if( std::string( argv[1] ) == "bst" )
113         mode =BST;
114     else if( std::string( argv[1] ) == "avl" )
115         mode =AVL;
116     else if( std::string( argv[1] ) == "treap" )
117         mode =TREAP;
118     if( std::string( argv[1] ) == "splay" )
119         mode =SPLAY;
120
121     if( !mode )
122         return printUsage( argv[0] );

```

```

123
124     std::ifstream fhaystack( argv[2] );
125     if( !fhaystack.good( ) ) {
126         std::cerr << "Could not open " << argv[2] << std::endl;
127         return -1;
128     }
129
130     std::ifstream fneedles( argv[3] );
131     if( !fneedles.good( ) ) {
132         std::cerr << "Could not open " << argv[3] << std::endl;
133         return -1;
134     }
135
136     if( argc == 5 ) {
137         if( argv[4] && mode != TREAP ) {
138             std::cerr << "This variable should only be set for Treaps." << std::endl;
139             return -1;
140         }
141         else if( atoi(argv[4]) <= 0 ) {
142             std::cerr << "This variable should only be an integer "
143                 << " greater than 0." << std::endl;
144             return -1;
145         }
146     }
147
148     std::vector<string> needles;
149     if( !extractNeedles( needles, fneedles ) ) {
150         cerr << "Could not read a set of strings to search for." << endl;
151         return -1;
152     }
153
154     BinarySearchTree<string> *tree;
155     switch( mode ) {
156         case BST:
157             tree = new BinarySearchTree<string>();
158             break;
159         case AVL:
160             tree = new AVLTree<string>();
161             break;
162         case SPLAY:
163             tree = new SplayTree<string>();
164             break;
165         case TREAP:
166             tree = new Treap<string>(atoi(argv[4]));
167             break;
168     }
169
170
171     // Define a start point to time measurement
172     auto start = std::chrono::system_clock::now();
173
174
175     if( !fillTree( tree, fhaystack ) ) {
176         cerr << "Could not read the haystack." << endl;

```

```

177         return -1;
178     }
179
180     // Determine the duration of the code block
181     auto duration =std::chrono::duration_cast<std::chrono::milliseconds>
182         (std::chrono::system_clock::now() - start);
183
184     cout << "Filled the binary search tree in " << duration.count() << "ms" << endl;
185
186     start = std::chrono::system_clock::now();
187     findAll( needles, tree );
188     duration =std::chrono::duration_cast<std::chrono::milliseconds>
189         (std::chrono::system_clock::now() - start);
190
191     cout << "Searched the haystack in " << duration.count() << "ms" << endl;
192
193     // Test pre-order
194     //for( auto word : *tree ) {
195     //    cout << word << '\n';
196     //}
197
198     fhaystack.close( );
199     fneedles.close( );
200     delete tree;
201
202     return 0;
203 }

```

### 6.3 Tree.h

```

1  /**
2   * Tree:
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file tree.h
7   * @date 26-10-2014
8   */
9
10 #ifndef TREE_H
11 #define TREE_H
12 #include "TreeNodeIterator.h"
13 #include <assert.h>
14 #include <list>
15 #include <map>
16
17 using namespace std;
18
19 template <class INFO_T> class SplayTree;
20
21 template <class INFO_T> class Tree
22 {
23     public:
24         enum ReplaceBehaviour {

```

```

25         DELETE_EXISTING,
26         ABORT_ON_EXISTING,
27         MOVE_EXISTING
28     };
29
30     typedef TreeNode<INFO_T> node_t;
31     typedef TreeNodeIterator<INFO_T> iterator;
32     typedef TreeNodeIterator_in<INFO_T> iterator_in;
33     typedef TreeNodeIterator_pre<INFO_T> iterator_pre;
34     typedef TreeNodeIterator_post<INFO_T> iterator_post;
35     typedef list<node_t*> nodelist;
36
37     /**
38      * @function   Tree( )
39      * @abstract   Constructor of an empty tree
40      **/
41     Tree( )
42     : m_root( 0 ) {
43     }
44
45     /**
46      * @function   Tree( )
47      * @abstract   Copy-constructor of a tree. The new tree contains the nodes
48      *             from the tree given in the parameter (deep copy)
49      * @param      tree, a tree
50      **/
51     Tree( const Tree<INFO_T>& tree )
52     : m_root( 0 ) {
53         *this =tree;
54     }
55
56     /**
57      * @function   ~Tree( )
58      * @abstract   Destructor of a tree. Timber.
59      **/
60     ~Tree( ) {
61         clear( );
62     }
63
64     /**
65      * @function   begin_pre( )
66      * @abstract   begin point for pre-order iteration
67      * @return     iterator_pre containing the beginning of the tree in
68      *             pre-order
69      **/
70     iterator_pre begin_pre( ) {
71         // Pre-order traversal starts at the root
72         return iterator_pre( m_root );
73     }
74
75     /**
76      * @function   begin( )
77      * @abstract   begin point for a pre-order iteration
78      * @return     containing the beginning of the pre-Order iteration

```

```

79      **/
80      iterator_pre begin( ) {
81          return begin_pre( );
82      }
83
84      /**
85      * @function   end( )
86      * @abstract   end point for a pre-order iteration
87      * @return     the end of the pre-order iteration
88      **/
89      iterator_pre end( ) {
90          return iterator_pre( (node_t*)0 );
91      }
92
93      /**
94      * @function   end_pre( )
95      * @abstract   end point for pre-order iteration
96      * @return     iterator_pre containing the end of the tree in pre-order
97      **/
98      iterator_pre end_pre( ) {
99          return iterator_pre( (node_t*)0 );
100     }
101
102     /**
103     * @function   begin_in( )
104     * @abstract   begin point for in-order iteration
105     * @return     iterator_in containing the beginning of the tree in
106     *             in-order
107     **/
108     iterator_in begin_in( ) {
109         if( !m_root )
110             return end_in( );
111         node_t *n =m_root;
112         while( n->leftChild( ) )
113             n =n->leftChild( );
114         return iterator_in( n );
115     }
116
117     /**
118     * @function   end_in( )
119     * @abstract   end point for in-order iteration
120     * @return     iterator_in containing the end of the tree in in-order
121     **/
122     iterator_in end_in( ) {
123         return iterator_in( (node_t*)0 );
124     }
125
126     /**
127     * @function   begin_post( )
128     * @abstract   begin point for post-order iteration
129     * @return     iterator_post containing the beginning of the tree in
130     *             post-order
131     **/
132     iterator_post begin_post( ) {

```

```

133         if( !m_root )
134             return end_post( );
135         node_t *n =m_root;
136         while( n->leftChild( ) )
137             n =n->leftChild( );
138         return iterator_post( n );
139     }
140
141 /**
142  * @function   end_post( )
143  * @abstract   end point for post-order iteration
144  * @return     iterator_post containing the end of the tree in post-order
145  */
146     iterator_post end_post( ) {
147         return iterator_post( (node_t*)0 );
148     }
149
150 /**
151  * @function   pushBack( )
152  * @abstract   a new TreeNode containing 'info' is added to the end
153  *             the node is added to the node that :
154  *             - is in the row as close to the root as possible
155  *             - has no children or only a left-child
156  *             - seen from the right hand side of the row
157  *             this is the 'natural' left-to-right filling order
158  *             compatible with array-based heaps and full b-trees
159  * @param      info, the contents of the new node
160  * @post       A node has been added.
161  */
162     virtual node_t *pushBack( const INFO_T& info ) {
163         node_t *n =new node_t( info, 0 );
164         if( !m_root ) { // Empty tree, simplest case
165             m_root =n;
166         }
167         else { // Leaf node, there are two different scenarios
168             int max =getRowCountRecursive( m_root, 0 );
169             node_t *parent;
170             for( int i =1; i <= max; ++i ) {
171
172                 parent =getFirstEmptySlot( i );
173                 if( parent ) {
174                     if( !parent->leftChild( ) )
175                         parent->setLeftChild( n );
176                     else if( !parent->rightChild( ) )
177                         parent->setRightChild( n );
178                     n->setParent( parent );
179                     break;
180                 }
181             }
182         }
183         return n;
184     }
185
186 /**

```

```

187      * @function      insert( )
188      * @abstract      inserts node or subtree under a parent or creates an empty
189      *                  root node
190      * @param          info, contents of the new node
191      * @param          parent, parent node of the new node. When zero, the root is
192      *                  assumed
193      * @param          alignRight, insert() checks on which side of the parent
194      *                  node the new node can be inserted. By default, it checks
195      *                  the left side first.
196      *                  To change this behavior, set preferRight =true.
197      * @param          replaceBehavior, action if parent already has two children.
198      *                  One of:
199      *                  ABORT_ON_EXISTING - abort and return zero
200      *                  MOVE_EXISTING - make the parent's child a child of the new
201      *                  node, satisfies preferRight
202      *                  DELETE_EXISTING - remove one of the children of parent
203      *                  completely also satisfies preferRight
204      * @return          pointer to the inserted TreeNode, if insertion was
205      *                  successfull
206      * @pre             If the tree is empty, a root node will be created with info
207      *                  as it contents
208      * @pre             The instance pointed to by parent should be part of the
209      *                  called instance of Tree
210      * @post            Return zero if no node was created. Ownership is assumed on
211      *                  the new node.
212      *                  When DELETE_EXISTING is specified, the entire subtree on
213      *                  preferred side may be deleted first.
214      **/
215      virtual node_t* insert( const INFO_T& info,
216                             node_t* parent =0,
217                             bool preferRight =false,
218                             int replaceBehavior =ABORT_ON_EXISTING ) {
219          if( !parent )
220              parent =m_root;
221
222          if( !parent )
223              return pushBack( info );
224
225          node_t *node =0;
226
227          if( !parent->leftChild( )
228              && ( !preferRight || ( preferRight &&
229                                     parent->rightChild( ) ) ) ) {
230              node =new node_t( info, parent );
231              parent->setLeftChild( node );
232              node->setParent( parent );
233
234          } else if( !parent->rightChild( ) ) {
235              node =new node_t( info, parent );
236              parent->setRightChild( node );
237              node->setParent( parent );
238
239          } else if( replaceBehavior == MOVE_EXISTING ) {
240              node =new node_t( info, parent );

```



```

241         if( preferRight ) {
242             node->setRightChild( parent->rightChild( ) );
243             node->rightChild( )->setParent( node );
244             parent->setRightChild( node );
245         } else {
246             node->setLeftChild( parent->leftChild( ) );
247             node->leftChild( )->setParent( node );
248             parent->setLeftChild( node );
249         }
250
251     } else if( replaceBehavior == DELETE_EXISTING ) {
252         node =new node_t( info, parent );
253         if( preferRight ) {
254             deleteRecursive( parent->rightChild( ) );
255             parent->setRightChild( node );
256         } else {
257             deleteRecursive( parent->leftChild( ) );
258             parent->setLeftChild( node );
259         }
260
261     }
262     return node;
263 }
264
265 /**
266  * @function replace( )
267  * @abstract replaces an existing node with a new node
268  * @param info, contents of the new node
269  * @param node, node to be replaced. When zero, the root is assumed
270  * @param alignRight, only for MOVE_EXISTING. If true, node will be
271  * the right child of the new node. Otherwise, it will be the
272  * left.
273  * @param replaceBehavior, one of:
274  * ABORT_ON_EXISTING - undefined for replace()
275  * MOVE_EXISTING - make node a child of the new node,
276  * satisfies preferRight
277  * DELETE_EXISTING - remove node completely
278  * @return pointer to the inserted TreeNode, replace() is always
279  * successful
280  * @pre If the tree is empty, a root node will be created with info
281  * as it contents
282  * @pre The instance pointed to by node should be part of the
283  * called instance of Tree
284  * @post Ownership is assumed on the new node. When DELETE_EXISTING
285  * is specified, the entire subtree pointed to by node is
286  * deleted first.
287  */
288 virtual node_t* replace( const INFO_T& info,
289                         node_t* node =0,
290                         bool alignRight =false ,
291                         int replaceBehavior =DELETE_EXISTING ) {
292     assert( replaceBehavior != ABORT_ON_EXISTING );
293
294     node_t *newnode =new node_t( info );

```

```

295         if( !node )
296             node =m_root;
297         if( !node )
298             return pushBack( info );
299
300         if( node->parent( ) ) {
301             newnode->setParent( node->parent( ) );
302             if( node->parent( )->leftChild( ) == node )
303                 node->parent( )->setLeftChild( newnode );
304             else
305                 node->parent( )->setRightChild( newnode );
306         } else
307             m_root =newnode;
308
309         if( replaceBehavior == DELETE_EXISTING ) {
310
311             deleteRecursive( node );
312         }
313         else if( replaceBehavior == MOVE_EXISTING ) {
314             if( alignRight )
315                 newnode->setRightChild( node );
316             else
317                 newnode->setLeftChild( node );
318             node->setParent( newnode );
319         }
320         return node;
321     }
322
323     /**
324     * @function   remove( )
325     * @abstract   removes and deletes node or subtree
326     * @param      n, node or subtree to be removed and deleted
327     * @post       after remove(), n points to an invalid address
328     */
329     virtual void remove( node_t *n ) {
330         if( !n )
331             return;
332         if( n->parent( ) ) {
333             if( n->parent( )->leftChild( ) == n )
334                 n->parent( )->setLeftChild( 0 );
335             else if( n->parent( )->rightChild( ) == n )
336                 n->parent( )->setRightChild( 0 );
337         }
338         deleteRecursive( n );
339     }
340
341     /**
342     * @function   clear( )
343     * @abstract   clears entire tree
344     * @pre        tree may be empty
345     * @post       all nodes and data are deallocated
346     */
347     void clear( ) {
348         deleteRecursive( m_root );

```

```

349         m_root =0;
350     }
351
352     /**
353     * @function  empty( )
354     * @abstract  test if tree is empty
355     * @return    true when empty
356     **/
357     bool isEmpty( ) const {
358         return !m_root;
359     }
360
361     /**
362     * @function  root( )
363     * @abstract  returns address of the root of the tree
364     * @return    the adress of the root of the tree is returned
365     * @pre       there needs to be a tree
366     **/
367     node_t* root( ){
368         return m_root;
369     }
370
371     /**
372     * @function  row( )
373     * @abstract  returns an entire row/level in the tree
374     * @param     level, the desired row. Zero gives just the root.
375     * @return    a list containing all node pointers in that row
376     * @pre       level must be positive or zero
377     * @post
378     **/
379     nodelist row( int level ) {
380         nodelist rlist;
381         getRowRecursive( m_root, rlist, level );
382         return rlist;
383     }
384
385     /**
386     * @function  find( )
387     * @abstract  find the first occurrence of info and returns its node ptr
388     * @param     haystack, the root of the (sub)tree we want to look in
389     *            null if we want to start at the root of the tree
390     * @param     needle, the needle in our haystack
391     * @return    a pointer to the first occurrence of needle
392     * @post      there may be multiple occurrences of needle, we only return
393     *            one. A null-pointer is returned if no needle is found
394     **/
395     virtual node_t* find( node_t* haystack, const INFO_T& needle ) {
396         if( haystack == 0 ) {
397             if( m_root )
398                 haystack =m_root;
399             else
400                 return 0;
401         }
402         return findRecursive( haystack, needle );

```

```

403     }
404
405 /**
406  * @function   contains( )
407  * @abstract   determines if a certain content (needle) is found
408  * @param      haystack, the root of the (sub)tree we want to look in
409  *             null if we want to start at the root of the tree
410  * @param      needle, the needle in our haystack
411  * @return     true if needle is found
412  */
413 bool contains( node_t* haystack, const INFO_T& needle ) {
414     return find( haystack, needle );
415 }
416
417 /**
418  * @function   toDot( )
419  * @abstract   writes tree in Dot-format to a stream
420  * @param      out, ostream to write to
421  * @pre        out must be a valid stream
422  * @post       out (file or cout) with the tree in dot-notation
423  */
424 void toDot( ostream& out, const string & graphName ) {
425     if( isEmpty( ) )
426         return;
427     map<node_t *, int> addresses;
428     typename map< node_t *, int >::iterator adrIt;
429     int i =1;
430     int p;
431     iterator_pre it;
432     iterator_pre tempit;
433     addresses[m_root] =0;
434     out << "digraph " << graphName << ' ' << endl << "' ' << 0 << "' ";
435     for( it =begin_pre( ); it != end_pre( ); ++it ) {
436         adrIt =addresses.find( &(*it) );
437         if( adrIt == addresses.end( ) ) {
438             addresses[&(*it)] =i;
439             p =i;
440             i ++;
441         }
442         if( (&(*it))->parent( ) != &(*tempit) )
443             out << ' ' << endl << "' '
444                 << addresses.find( (&(*it))->parent( ))->second << "' ";
445         if( (&(*it)) != m_root )
446             out << " -> \" << p << "' ";
447         tempit =it;
448     }
449     out << ' ' << endl;
450     for ( adrIt =addresses.begin( ); adrIt != addresses.end( ); ++adrIt )
451         out << adrIt->second << " [label=\"
452             << adrIt->first->info( ) << "\"]";
453     out << ' } ' ;
454 }
455
456 /**

```

```

457     * @function    copyFromNode( )
458     * @abstract    copies the the node source and its children to the node
459     *               dest
460     * @param        source, the node and its children that need to be copied
461     * @param        dest, the node who is going to get the copied children
462     * @param        left, this is true if it's a left child.
463     * @pre          there needs to be a tree and we can't copy to a root.
464     * @post         the subtree that starts at source is now also a child of
465     *               dest
466     **/
467     void copyFromNode( node_t *source, node_t *dest, bool left ) {
468         if (!source)
469             return;
470         node_t *acorn = new node_t( dest );
471         if(left) {
472             if( dest->leftChild( ))
473                 return;
474             dest->setLeftChild( acorn );
475         }
476         else {
477             if( dest->rightChild( ))
478                 return;
479             dest->setRightChild( acorn );
480         }
481         cloneRecursive( source, acorn );
482     }
483
484     Tree<INFO_T>& operator=( const Tree<INFO_T>& tree ) {
485         clear( );
486         if( tree.m_root ) {
487             m_root = new node_t( (node_t*)0 );
488             cloneRecursive( tree.m_root, m_root );
489         }
490         return *this;
491     }
492
493 protected:
494     /**
495     * @function    cloneRecursive( )
496     * @abstract    cloning a subtree to a node
497     * @param        source, the node we want to start the cloning process from
498     * @param        dest, the node we want to clone to
499     * @post         the subtree starting at source is cloned to the node dest
500     **/
501     void cloneRecursive( node_t *source, node_t* dest ) {
502         dest->info() =source->info();
503         if( source->leftChild( ) ) {
504             node_t *left =new node_t( dest );
505             dest->setLeftChild( left );
506             cloneRecursive( source->leftChild( ), left );
507         }
508         if( source->rightChild( ) ) {
509             node_t *right =new node_t( dest );
510             dest->setRightChild( right );

```

```

511         cloneRecursive( source->rightChild( ), right );
512     }
513 }
514
515 /**
516  * @function   deleteRecursive( )
517  * @abstract   delete all nodes of a given tree
518  * @param      root, starting point, is deleted last
519  * @post       the subtree has been deleted
520  */
521 void deleteRecursive( node_t *root ) {
522     if( !root )
523         return;
524     deleteRecursive( root->leftChild( ) );
525     deleteRecursive( root->rightChild( ) );
526     delete root;
527 }
528
529 /**
530  * @function   getRowCountRecursive( )
531  * @abstract   calculate the maximum depth/row count in a subtree
532  * @param      root, starting point
533  * @param      level, starting level
534  * @return     maximum depth/rows in the subtree
535  */
536 int getRowCountRecursive( node_t* root, int level ) {
537     if( !root )
538         return level;
539     return max(
540         getRowCountRecursive( root->leftChild( ), level+1 ),
541         getRowCountRecursive( root->rightChild( ), level+1 ) );
542 }
543
544 /**
545  * @function   getRowRecursive( )
546  * @abstract   compile a full list of one row in the tree
547  * @param      root, starting point
548  * @param      rlist, reference to the list so far
549  * @param      level, how many level still to go
550  * @post       a list of a row in the tree has been made.
551  */
552 void getRowRecursive( node_t* root, nodelist &rlist, int level ) {
553     // Base-case
554     if( !level ) {
555         rlist.push_back( root );
556     } else if( root ){
557         level--;
558         if( level && !root->leftChild( ) )
559             for( int i =0; i < (level<<1); ++i )
560                 rlist.push_back( 0 );
561         else
562             getRowRecursive( root->leftChild( ), rlist, level );
563
564         if( level && !root->rightChild( ) )

```

```

565         for( int i =0; i < (level<<1); ++i )
566             rlist.push_back( 0 );
567     else
568         getRowRecursive( root->rightChild( ), rlist, level );
569     }
570 }
571
572 /**
573  * @function findRecursive( )
574  * @abstract first the first occurrence of needle and return its node
575  * ptr
576  * @param haystack, root of the search tree
577  * @param needle, copy of the data to find
578  * @return the node that contains the needle
579  */
580 node_t *findRecursive( node_t* haystack, const INFO_T &needle ) {
581     if( haystack->info( ) == needle )
582         return haystack;
583
584     node_t *n =0;
585     if( haystack->leftChild( ) )
586         n =findRecursive( haystack->leftChild( ), needle );
587     if( !n && haystack->rightChild( ) )
588         n =findRecursive( haystack->rightChild( ), needle );
589     return n;
590 }
591
592 friend class TreeNodeIterator_pre<INFO_T>;
593 friend class TreeNodeIterator_in<INFO_T>;
594 friend class SplayTree<INFO_T>;
595 TreeNode<INFO_T> *m_root;
596
597 private:
598 /**
599  * @function getFirstEmptySlot( )
600  * @abstract when a row has a continuous empty space on the right,
601  * find the left-most parent in the above row that has
602  * at least one empty slot.
603  * @param level, how many level still to go
604  * @return the first empty slot where we can put a new node
605  * @pre level should be > 1
606  */
607 node_t *getFirstEmptySlot( int level ) {
608     node_t *p =0;
609     nodelist rlist =row( level-1 ); // we need the parents of this level
610     /** changed auto to int */
611     for( auto it =rlist.rbegin( ); it !=rlist.rend( ); ++it ) {
612         if( !(*it)->hasChildren( ) )
613             p =(*it);
614         else if( !(*it)->rightChild( ) ) {
615             p =(*it);
616             break;
617         } else
618             break;

```

```

619         }
620         return p;
621     }
622 };
623
624 #endif

```

## 6.4 TreeNode.h

```

1  /**
2   * Treenode:
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file   Treenode.h
7   * @date   26-10-2014
8   */
9
10 #ifndef TREENODE.H
11 #define TREENODE.H
12
13 using namespace std;
14
15 template <class INFO_T> class Tree;
16 class ExpressionTree;
17
18 template <class INFO_T> class TreeNode
19 {
20     public:
21         /**
22          * @function   TreeNode( )
23          * @abstract   Constructor, creates a node
24          * @param      info, the contents of a node
25          * @param      parent, the parent of the node
26          * @post       A node has been created.
27          */
28         TreeNode( const INFO_T& info, TreeNode<INFO_T>* parent =0 )
29             : m_lchild( 0 ), m_rchild( 0 ) {
30             m_info =info;
31             m_parent =parent;
32         }
33
34         /**
35          * @function   TreeNode( )
36          * @abstract   Constructor, creates a node
37          * @param      parent, the parent of the node
38          * @post       A node has been created.
39          */
40         TreeNode( TreeNode<INFO_T>* parent =0 )
41             : m_lchild( 0 ), m_rchild( 0 ) {
42             m_parent =parent;
43         }
44
45         /**

```



```

46     * @function      =
47     * @abstract      Sets a nodes content to N
48     * @param         n, the contents you want the node to have
49     * @post          The node now has those contents.
50     **/
51     void operator =( INFO_T n ) { m_info =n; }
52
53     /**
54     * @function      INFO_T( ), info( )
55     * @abstract      Returns the content of a node
56     * @return        m_info, the contents of the node
57     **/
58     operator INFO_T( ) const { return m_info; }
59     const INFO_T &info( ) const { return m_info; }
60     INFO_T &info( ) { return m_info; }
61     /**
62     * @function      atRow( )
63     * @abstract      returns the level or row-number of this node
64     * @return        row, an int of row the node is at
65     **/
66     int atRow( ) const {
67         const TreeNode<INFO_T> *n =this;
68         int row =0;
69         while( n->parent( ) ) {
70             n =n->parent( );
71             row++;
72         }
73         return row;
74     }
75
76     /**
77     * @function      parent( ), leftChild( ), rightChild( )
78     * @abstract      returns the adress of the parent, left child and right
79     *                 child respectively
80     * @return        the adress of the requested family member of the node
81     **/
82     TreeNode<INFO_T> *parent( ) const { return m_parent; }
83     TreeNode<INFO_T> *leftChild( ) const { return m_lchild; }
84     TreeNode<INFO_T> *rightChild( ) const { return m_rchild; }
85
86     /**
87     * @function      swapWith( )
88     * @abstract      Swaps this node with another node in the tree
89     * @param         n, the node to swap this one with
90     * @pre           both this node and n must be in the same parent tree
91     * @post          n will have the parent and children of this node
92     *                 and vice verse. Both nodes retain their data.
93     **/
94     void swapWith( TreeNode<INFO_T>* n ) {
95         bool this_wasLeftChild =false, n_wasLeftChild =false;
96         if( parent( ) && parent( )->leftChild( ) == this )
97             this_wasLeftChild =true;
98         if( n->parent( ) && n->parent( )->leftChild( ) == n )
99             n_wasLeftChild =true;

```

```

100
101 // Swap the family info
102 TreeNode<INFO_T>* newParent =
103     ( n->parent( ) == this ) ? n : n->parent( );
104 TreeNode<INFO_T>* newLeft =
105     ( n->leftChild( ) == this ) ? n : n->leftChild( );
106 TreeNode<INFO_T>* newRight =
107     ( n->rightChild( ) == this ) ? n : n->rightChild( );
108
109 n->setParent( parent( ) == n ? this : parent( ) );
110 n->setLeftChild( leftChild( ) == n ? this : leftChild( ) );
111 n->setRightChild( rightChild( ) == n ? this : rightChild( ) );
112
113 setParent( newParent );
114 setLeftChild( newLeft );
115 setRightChild( newRight );
116
117 // Restore applicable pointers
118 if( n->leftChild( ) )
119     n->leftChild( )->setParent( n );
120 if( n->rightChild( ) )
121     n->rightChild( )->setParent( n );
122 if( leftChild( ) )
123     leftChild( )->setParent( this );
124 if( rightChild( ) )
125     rightChild( )->setParent( this );
126 if( n->parent( ) ) {
127     if( this_wasLeftChild )
128         n->parent( )->setLeftChild( n );
129     else
130         n->parent( )->setRightChild( n );
131 }
132 if( parent( ) ) {
133     if( n_wasLeftChild )
134         parent( )->setLeftChild( this );
135     else
136         parent( )->setRightChild( this );
137 }
138 }
139
140 /**
141 * @function replace( )
142 * @abstract Replaces the node with another node in the tree
143 * @param n, the node we replace the node with, this one gets deleted
144 * @pre both this node and n must be in the same parent tree
145 * @post The node will be replaced and n will be deleted.
146 */
147 void replace( TreeNode<INFO_T>* n ) {
148     bool n_wasLeftChild =false;
149
150     if( n->parent( ) && n->parent( )->leftChild( ) == n )
151         n_wasLeftChild =true;
152
153     // Swap the family info

```

```

154     TreeNode<INFO_T>* newParent =
155         ( n->parent( ) == this ) ? n : n->parent( );
156     TreeNode<INFO_T>* newLeft =
157         ( n->leftChild( ) == this ) ? n : n->leftChild( );
158     TreeNode<INFO_T>* newRight =
159         ( n->rightChild( ) == this ) ? n : n->rightChild( );
160
161     setParent( newParent );
162     setLeftChild( newLeft );
163     setRightChild( newRight );
164     m_info = n->m_info;
165
166     // Restore applicable pointers
167     if( leftChild( ) )
168         leftChild( )->setParent( this );
169     if( rightChild( ) )
170         rightChild( )->setParent( this );
171
172     if( parent( ) ) {
173         if( n_wasLeftChild )
174             parent( )->setLeftChild( this );
175         else
176             parent( )->setRightChild( this );
177     }
178     delete n;
179 }
180
181 /**
182  * @function sibling( )
183  * @abstract returns the address of the sibling
184  * @return the address to the sibling or zero if there is no sibling
185  */
186     TreeNode<INFO_T>* sibling( ) {
187         if( parent( )->leftChild( ) == this )
188             return parent( )->rightChild( );
189         else if( parent( )->rightChild( ) == this )
190             return parent( )->leftChild( );
191         else
192             return 0;
193     }
194
195 /**
196  * @function hasChildren( ), hasParent( ), isFull( )
197  * @abstract Returns whether the node has children, has parents or is
198  *           full (has two children) respectively
199  * @param
200  * @return true or false, depending on what is requested from the node.
201  *         if hasChildren is called and the node has children, it will
202  *         return true, otherwise false.
203  *         If hasParent is called and the node has a parent, it will
204  *         return true, otherwise false.
205  *         If isFull is called and the node has two children, it will
206  *         return true, otherwise false.
207  */

```

```

208         bool hasChildren( ) const { return m_lchild || m_rchild; }
209         bool hasParent( ) const { return m_parent; }
210         bool isFull( ) const { return m_lchild && m_rchild; }
211
212     protected:
213         friend class Tree<INFO_T>;
214         friend class ExpressionTree;
215
216         /**
217          * @function   setParent( ), setLeftChild( ), setRightChild( )
218          * @abstract   sets the parent, left child and right child of the
219          *               particular node respectively
220          * @param       p, the node we want to set a certain family member of
221          * @return      void
222          * @post        The node now has a parent, a left child or a right child
223          *               respectively.
224          */
225         void setParent( TreeNode<INFO_T> *p ) { m_parent =p; }
226         void setLeftChild( TreeNode<INFO_T> *p ) { m_lchild =p; }
227         void setRightChild( TreeNode<INFO_T> *p ) { m_rchild =p; }
228
229     private:
230         INFO_T m_info;
231         TreeNode<INFO_T> *m_parent;
232         TreeNode<INFO_T> *m_lchild;
233         TreeNode<INFO_T> *m_rchild;
234 };
235
236 /**
237  * @function   <<
238  * @abstract   the contents of the node are returned
239  * @param       out, in what format we want to get the contents
240  * @param       rhs, the node of which we want the contents
241  * @return      the contents of the node.
242  */
243 template <class INFO_T> ostream &operator <<(ostream& out, const TreeNode<INFO_T> & r
244         out << rhs.info( );
245         return out;
246 }
247
248 #endif

```

## 6.5 TreeNodeIterator.h

```

1  /**
2   * TreeNodeIterator: Provides a set of iterators that follow the STL-standard
3   *
4   * @author   Micky Faas (s1407937)
5   * @author   Lisette de Schipper (s1396250)
6   * @file     TreeNodeIterator.h
7   * @date     26-10-2014
8   */
9
10 #include <iterator>

```

```

11 #include "TreeNode.h"
12
13 template <class INFO_T> class TreeNodeIterator
14     : public std::iterator<std::forward_iterator_tag,
15                             TreeNode<INFO_T>> {
16     public:
17         typedef TreeNode<INFO_T> node_t;
18
19         /**
20          * @function   TreeNodeIterator( )
21          * @abstract   (copy)constructor
22          * @pre        TreeNodeIterator is abstract and cannot be constructed
23          */
24         TreeNodeIterator( node_t* ptr =0 ) : p( ptr ) { }
25         TreeNodeIterator( const TreeNodeIterator& it ) : p( it.p ) { }
26
27         /**
28          * @function   (in)equality operator overload
29          * @abstract   Test (in)equality for two TreeNodeIterators
30          * @param      rhs, right-hand side of the comparison
31          * @return      true if both iterators point to the same node (==)
32          *              false if both iterators point to the same node (!=)
33          */
34         bool operator == (const TreeNodeIterator& rhs) { return p==rhs.p; }
35         bool operator != (const TreeNodeIterator& rhs) { return p!=rhs.p; }
36
37         /**
38          * @function   operator*( )
39          * @abstract   Cast operator to node_t reference
40          * @return      The value of the current node
41          * @pre        Must point to a valid node
42          */
43         node_t& operator*( ) { return *p; }
44
45         /**
46          * @function   operator++( )
47          * @abstract   pre- and post increment operators
48          * @return      TreeNodeIterator that has iterated one step
49          */
50         TreeNodeIterator &operator++( ) { next( ); return *this; }
51         TreeNodeIterator operator++( int )
52             { TreeNodeIterator tmp( *this ); operator++( ); return tmp; }
53     protected:
54
55         /**
56          * @function   next( ) //(pure virtual)
57          * @abstract   Implement this function to implement your own iterator
58          */
59         virtual bool next( ){ return false; }// =0;
60         node_t *p;
61     };
62
63     template <class INFO_T> class TreeNodeIterator_pre
64         : public TreeNodeIterator<INFO_T> {

```

```

65     public:
66         typedef TreeNode<INFO_T> node_t;
67
68         TreeNodeIterator_pre( node_t* ptr =0 )
69             : TreeNodeIterator<INFO_T>( ptr ) { }
70         TreeNodeIterator_pre( const TreeNodeIterator<INFO_T>& it )
71             : TreeNodeIterator<INFO_T>( it ) { }
72         TreeNodeIterator_pre( const TreeNodeIterator_pre& it )
73             : TreeNodeIterator<INFO_T>( it.p ) { }
74
75         TreeNodeIterator_pre &operator++( ) { next( ); return *this; }
76         TreeNodeIterator_pre operator++( int )
77             { TreeNodeIterator_pre tmp( *this ); operator++( ); return tmp; }
78
79     protected:
80         using TreeNodeIterator<INFO_T>::p;
81
82         /**
83          * @function next( )
84          * @abstract Takes one step in pre-order traversal
85          * @return returns true if such a step exists
86          */
87         bool next( ) {
88             if( !p )
89                 return false;
90             if( p->hasChildren( ) ) { // a possible child that can be the next
91                 p =p->leftChild( ) ? p->leftChild( ) : p->rightChild( );
92                 return true;
93             }
94             else if( p->hasParent( ) // we have a right brother
95                     && p->parent( )->rightChild( )
96                     && p->parent( )->rightChild( ) != p ) {
97                 p =p->parent( )->rightChild( );
98                 return true;
99             }
100             else if( p->hasParent( ) ) { // just a parent, thus we go up
101                 TreeNode<INFO_T> *tmp =p->parent( );
102                 while( tmp->parent( ) ) {
103                     if( tmp->parent( )->rightChild( )
104                         && tmp->parent( )->rightChild( ) != tmp ) {
105                         p =tmp->parent( )->rightChild( );
106                         return true;
107                     }
108                     tmp =tmp->parent( );
109                 }
110             }
111             // Nothing left
112             p =0;
113             return false;
114         }
115
116     };
117
118     template <class INFO_T> class TreeNodeIterator_in

```

```

119         : public TreeNodeIterator<INFO_T>{
120     public:
121         typedef TreeNode<INFO_T> node_t;
122
123         TreeNodeIterator_in( node_t* ptr =0 )
124             : TreeNodeIterator<INFO_T>( ptr ) { }
125         TreeNodeIterator_in( const TreeNodeIterator<INFO_T>& it )
126             : TreeNodeIterator<INFO_T>( it ) { }
127         TreeNodeIterator_in( const TreeNodeIterator_in& it )
128             : TreeNodeIterator<INFO_T>( it.p ) { }
129
130         TreeNodeIterator_in &operator++( ) { next( ); return *this; }
131         TreeNodeIterator_in operator++( int )
132             { TreeNodeIterator_in tmp( *this ); operator++( ); return tmp; }
133
134     protected:
135         using TreeNodeIterator<INFO_T>::p;
136         /**
137          * @function next( )
138          * @abstract Takes one step in in-order traversal
139          * @return returns true if such a step exists
140          */
141         bool next( ) {
142             if( p->rightChild( ) ) {
143                 p =p->rightChild( );
144                 while( p->leftChild( ) )
145                     p =p->leftChild( );
146                 return true;
147             }
148             else if( p->parent( ) && p->parent( )->leftChild( ) == p ) {
149                 p =p->parent( );
150                 return true;
151             } else if( p->parent( ) && p->parent( )->rightChild( ) == p ) {
152                 p =p->parent( );
153                 while( p->parent( ) && p == p->parent( )->rightChild( ) ) {
154                     p =p->parent( );
155                 }
156                 if( p )
157                     p =p->parent( );
158                 if( p )
159                     return true;
160                 else
161                     return false;
162             }
163             // Er is niks meer
164             p =0;
165             return false;
166         }
167     };
168
169     template <class INFO_T> class TreeNodeIterator_post
170         : public TreeNodeIterator<INFO_T>{
171     public:
172         typedef TreeNode<INFO_T> node_t;

```

```

173
174     TreeNodeIterator_post( node_t* ptr =0 )
175         : TreeNodeIterator<INFO_T>( ptr ) { }
176     TreeNodeIterator_post( const TreeNodeIterator<INFO_T>& it )
177         : TreeNodeIterator<INFO_T>( it ) { }
178     TreeNodeIterator_post( const TreeNodeIterator_post& it )
179         : TreeNodeIterator<INFO_T>( it.p ) { }
180
181     TreeNodeIterator_post &operator++( ) { next( ); return *this; }
182     TreeNodeIterator_post operator++( int )
183         { TreeNodeIterator_post tmp( *this ); operator++( ); return tmp; }
184
185     protected:
186         using TreeNodeIterator<INFO_T>::p;
187         /**
188          * @function next( )
189          * @abstract Takes one step in post-order traversal
190          * @return returns true if such a step exists
191          */
192         bool next( ) {
193
194             if( p->hasParent( ) // We have a right brother
195                 && p->parent( )->rightChild( )
196                 && p->parent( )->rightChild( ) != p ) {
197                 p =p->parent( )->rightChild( );
198                 while( p->leftChild( ) )
199                     p =p->leftChild( );
200                 return true;
201             } else if( p->parent( ) ) {
202                 p =p->parent( );
203                 return true;
204             }
205             // Nothing left
206             p =0;
207             return false;
208         }
209     };

```

## 6.6 SelfOrganizingTree.h

```

1  /**
2   * SelfOrganizingTree - Abstract base type inheriting from Tree
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file SelfOrganizingTree.h
7   * @date 3-11-2014
8   */
9
10 #ifndef SELFORGANIZINGTREE_H
11 #define SELFORGANIZINGTREE_H
12
13 #include "BinarySearchTree.h"
14

```



```

15 template <class INFO_T> class SelfOrganizingTree : public BinarySearchTree<INFO_T> {
16     public:
17         typedef BSTNode<INFO_T> node_t;
18         typedef BinarySearchTree<INFO_T> S; // super class
19
20         /**
21          * @function SelfOrganizingTree( ) : S( )
22          * @abstract Constructor
23          */
24         SelfOrganizingTree( ) : S( ) { }
25
26         /**
27          * @function rotateLeft( ) and rotateRight( )
28          * @abstract Performs a rotation with the given node as root of the
29          *           rotating subtree, either left of right.
30          *           The tree's root pointer will be updated if necessary.
31          * @param node, the node to rotate
32          * @pre The node must be a node in this tree
33          * @post The node may be the new root of the tree
34          *       No nodes will be invalidated and no new memory is
35          *       allocated. Iterators may become invalid.
36          */
37         virtual node_t *rotateLeft( node_t * node ){
38             if( this->root( ) == node )
39                 return static_cast<node_t *>( S::m_root = node->rotateLeft( ) );
40             else
41                 return node->rotateLeft( );
42         }
43
44         virtual node_t *rotateRight( node_t * node ){
45             if( this->root( ) == node )
46                 return static_cast<node_t *>( S::m_root = node->rotateRight( ) );
47             else
48                 return node->rotateRight( );
49         }
50
51     private:
52
53 };
54
55
56 #endif

```

## 6.7 BinarySearchTree.h

```

1  /**
2   * BinarySearchTree - BST that inherits from Tree
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file BinarySearchTree.h
7   * @date 3-11-2014
8   */
9

```

```

10 #ifndef BINARYSEARCHTREE_H
11 #define BINARYSEARCHTREE_H
12
13 #include "Tree.h"
14 #include "BSTNode.h"
15
16 template <class INFO_T> class BinarySearchTree : public Tree<INFO_T> {
17     public:
18         typedef BSTNode<INFO_T> node_t;
19         typedef Tree<INFO_T> S; // super class
20
21         BinarySearchTree( ) : S( ) { }
22         BinarySearchTree( const BinarySearchTree& cpy ) : S( cpy ) { }
23
24         virtual ~BinarySearchTree( ) { }
25
26     /**
27      * @function   pushBack( )
28      * @abstract   reimplemented virtual function from Tree<>
29      *             this function is semantically identical to insert()
30      * @param      info, the contents of the new node
31      */
32     virtual node_t *pushBack( const INFO_T& info ) {
33         return insert( info );
34     }
35
36     /**
37      * @function   insert( )
38      * @abstract   reimplemented virtual function from Tree<>
39      *             the exact location of the new node is determined
40      *             by the rules of the binary search tree.
41      * @param      info, the contents of the new node
42      * @param      parent, ignored
43      * @param      preferRight, ignored
44      * @param      replaceBehavior, ignored
45      * @return      returns a pointer to the inserted node
46      */
47     virtual node_t* insert( const INFO_T& info,
48                             TreeNode<INFO_T>* parent =0, // Ignored
49                             bool preferRight =false,      // Ignored
50                             int replaceBehavior =S::ABORT_ON_EXISTING ) { // Ignored
51         node_t *n =new node_t( );
52         return insertInto( info, n );
53     }
54
55     /**
56      * @function   replace( )
57      * @abstract   reimplemented virtual function from Tree<>
58      *             replaces a given node or the root
59      *             the location of the replaced node may be different
60      *             due to the consistency of the binary search tree
61      * @param      info, the contents of the new node
62      * @param      node, node to be replaced
63      * @param      alignRight, ignored

```

```

64      * @param      replaceBehavior, ignored
65      * @return      returns a pointer to the new node
66      * @pre         node should be in this tree
67      * @post        replace() will delete and/or remove node.
68      *              if node is 0, it will take the root instead
69      **/
70      virtual node_t* replace( const INFO_T& info,
71                              TreeNode<INFO_T>* node =0,
72                              bool alignRight =false,
73                              int replaceBehavior =S::DELETE_EXISTING ) {
74          node_t *newnode;
75          if( !node )
76              node =S::m_root;
77          if( !node )
78              return pushBack( info );
79
80          bool swap =false;
81          // We can either just swap the new node with the old and remove
82          // the old, or we can remove the old and add the new node via
83          // pushBack(). This depends on the value of info
84          if( !node->hasChildren( ) ) {
85              swap =true;
86          }
87          else if( !(node->leftChild( )
88                  && node->leftChild( )->info( ) > info )
89                  && !(node->rightChild( )
90                  && node->rightChild( )->info( ) < info ) ) {
91              swap =true;
92          }
93          if( swap ) {
94              newnode =new node_t( info );
95              if( node == S::m_root )
96                  S::m_root =newnode;
97              node->swapWith( newnode );
98              delete node;
99          } else {
100              remove( node );
101              newnode =pushBack( info );
102
103          }
104          return newnode;
105      }
106
107      /**
108      * @function      remove( )
109      * @abstract      reimplemented virtual function from Tree<>
110      *                removes a given node or the root and restores the
111      *                BST properties
112      * @param          node, node to be removed
113      * @pre            node should be in this tree
114      * @post           memory for node will be deallocated
115      **/
116      virtual void remove( TreeNode<INFO_T> *node ) {
117          node_t *n =static_cast<node_t*>( node );

```

```

118
119
120         while( n->isFull( ) ) {
121             // the difficult case
122             // we could take either left of right here
123             TreeNode<INFO_T> *temp;
124             temp =n->leftChild( );
125             while( temp->rightChild( ) ) {
126                 temp =temp->rightChild( );
127             }
128             if( n == S::m_root )
129                 S::m_root =temp;
130             n->swapWith( temp );
131         }
132
133         // Assume the above is fixed
134         while( n->hasChildren( ) ) {
135             if( n->leftChild( ) ) {
136                 if( n == S::m_root )
137                     S::m_root =n->leftChild( );
138                 n->swapWith( n->leftChild( ) );
139             }
140             else {
141                 if( n == S::m_root )
142                     S::m_root =n->rightChild( );
143                 n->swapWith( n->rightChild( ) );
144             }
145         }
146
147         if( n->parent( ) && n->parent( )->leftChild( ) == n )
148             static_cast<node_t*>( n->parent( ) )->setLeftChild( 0 );
149         else if( n->parent( ) && n->parent( )->rightChild( ) == n )
150             static_cast<node_t*>( n->parent( ) )->setRightChild( 0 );
151         delete n;
152     }
153
154 /**
155  * @function   find( )
156  * @abstract   reimplemented virtual function from Tree<>
157  *             performs a binary search in a given (sub)tree
158  * @param      haystack, the subtree to search. Give 0 for the entire tree
159  * @param      needle, key/info-value to find
160  * @return     returns a pointer to node, if found
161  * @pre        haystack should be in this tree
162  * @post       may return 0
163  */
164 virtual TreeNode<INFO_T>* find( TreeNode<INFO_T>* haystack,
165                                const INFO_T& needle ) {
166     m_searchStepCounter =0;
167
168     if( !haystack )
169         haystack =S::m_root;
170     while( haystack && haystack->info( ) != needle ) {
171         m_searchStepCounter++;

```

```

172         if( haystack->info( ) > needle )
173             haystack =haystack->leftChild( );
174         else
175             haystack =haystack->rightChild( );
176     }
177     if( !haystack )
178         m_searchStepCounter =-1;
179     return haystack;
180 }
181
182 /**
183  * @function    lastSearchStepCount( )
184  * @abstract    gives the amount of steps needed to complete the most
185  *              recent call to find( )
186  * @return       positive amount of steps on a defined search result,
187  *              -1 on no search result
188  */
189 virtual int lastSearchStepCount( ) const {
190     return m_searchStepCounter;
191 }
192
193 /**
194  * @function    min( )
195  * @abstract    Returns the node with the least value in a binary search
196  *              tree. This is achieved through recursion.
197  * @param        node - the node from which we start looking
198  * @return       Eventually, at the end of the recursion, we return the
199  *              adress of the node with the smallest value.
200  * @post        The node with the smallest value is returned.
201  */
202 node_t* min( node_t* node ) const {
203     return node->leftChild( ) ?
204         min(static_cast<node_t*>( node->leftChild( ) ) ) : node;
205 }
206
207 /**
208  * @function    min( )
209  * @abstract    We call the function mentioned above and then
210  *              return the node with the least value in a binary search
211  *              tree.
212  * @return       We return the adress of the node with the smallest value.
213  * @post        The node with the smallest value is returned.
214  */
215 node_t* min( ) const {
216     return min( static_cast<node_t*>( this->root( ) ) );
217 }
218
219 /**
220  * @function    max( )
221  * @abstract    Returns the node with the highest value in a binary
222  *              search tree. This is achieved through recursion.
223  * @param        node - the node from which we start looking
224  * @return       Eventually, at the end of the recursion, we return the
225  *              adress of the node with the highest value.

```

```

226      * @post          The node with the highest value is returned.
227      **/
228      node_t* max( node_t* node ) const {
229          return node->rightChild( ) ?
230              max(static_cast<node_t*>( node->rightChild( ) ) ) : node;
231      }
232
233      /**
234      * @function      max( )
235      * @abstract      We call the function mentioned above and then
236      *                return the node with the highest value in a binary
237      *                search tree.
238      * @return         We return the address of the node with the highest value.
239      * @post           The node with the highest value is returned.
240      **/
241      node_t* max( ) const {
242          return max( static_cast<node_t*>( this->root( ) ) );
243      }
244
245  protected:
246      /**
247      * @function      insertInto( )
248      * @abstract      Inserts new node into the tree following BST rules
249      *                Assumes that the memory for the node is already allocated
250      *                This function exists mainly because of derived classes
251      *                want to insert nodes of a derived type.
252      * @param          info, the contents of the new node
253      * @param          n, node pointer, should be already allocated
254      * @return         returns a pointer to the inserted node
255      **/
256      virtual node_t* insertInto( const INFO_T& info,
257                                  node_t* n ) { // Preallocated
258          n->info() =info;
259
260          if( !S::m_root )
261              S::m_root =n;
262          else {
263              node_t *parent =0;
264              node_t *sub =static_cast<node_t*>( S::m_root );
265              do {
266                  if( *n < *sub ) {
267                      parent =sub;
268                      sub =static_cast<node_t*>( parent->leftChild( ) );
269                  }
270                  else {
271                      parent =sub;
272                      sub =static_cast<node_t*>( parent->rightChild( ) );
273                  }
274              } while( sub );
275              if( *n < *parent )
276                  parent->setLeftChild( n );
277              else
278                  parent->setRightChild( n );
279              n->setParent( parent );

```

```

280         }
281         return n;
282     }
283
284     int m_searchStepCounter;
285 };
286
287 #endif

```

## 6.8 BSTNode.h

```

1  /**
2   * BSTNode - Node atom for BinarySearchTree
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file BSTNode.h
7   * @date 3-11-2014
8   */
9
10 #ifndef BSTNODE_H
11 #define BSTNODE_H
12
13 #include "TreeNode.h"
14
15 template <class INFO_T> class BinarySearchTree;
16
17 template <class INFO_T> class BSTNode : public TreeNode<INFO_T>
18 {
19     public:
20         typedef TreeNode<INFO_T> S; // super class
21
22         /**
23          * @function BSTNode( )
24          * @abstract Constructor, creates a node
25          * @param info, the contents of a node
26          * @param parent, the parent of the node
27          * @post A node has been created.
28          */
29         BSTNode( const INFO_T& info, BSTNode<INFO_T>* parent =0 )
30             : S( info, parent ) { }
31
32         /**
33          * @function BSTNode( )
34          * @abstract Constructor, creates a node
35          * @param parent, the parent of the node
36          * @post A node has been created.
37          */
38         BSTNode( BSTNode<INFO_T>* parent =0 )
39             : S( (S)parent ) { }
40
41         // Idea: rotate this node left and return the node that comes in its place
42         BSTNode *rotateLeft( ) {
43

```

```

44         if( !this->rightChild( ) ) // Cannot rotate
45             return this;
46
47         bool isLeftChild =this->parent( ) && this == this->parent( )->leftChild(
48
49         // new root of tree
50         BSTNode *newTop =static_cast<BSTNode *>(this->rightChild( ));
51         // new rightchild of the node that is rotated
52         BSTNode *newRight =static_cast<BSTNode *>(newTop->leftChild( ));
53         // the parent under which all of the magic is happening
54         BSTNode *topParent =static_cast<BSTNode *>(this->parent( ));
55
56         // We become left-child of our right-child
57         // newTop takes our place with our parent
58         newTop->setParent( topParent );
59         if( isLeftChild && topParent )
60             topParent->setLeftChild( newTop );
61         else if( topParent )
62             topParent->setRightChild( newTop );
63
64         newTop->setLeftChild( this );
65         this->setParent( newTop );
66
67         // We take the left-child of newTop as our right-child
68         this->setRightChild( newRight );
69         if( newRight )
70             newRight->setParent( this );
71
72         return newTop;
73     }
74
75     // Idea: rotate this node right and return the node that comes in its place
76     BSTNode *rotateRight( ) {
77         if( !this->leftChild( ) ) // Cannot rotate
78             return this;
79
80         bool isRightChild =this->parent( ) && this == this->parent( )->rightChild
81
82         // new root of tree
83         BSTNode *newTop =static_cast<BSTNode *>(this->leftChild( ));
84         // new leftchild of the node that is rotated
85         BSTNode *newLeft =static_cast<BSTNode *>(newTop->rightChild( ));
86         // the parent under which all of the magic is happening
87         BSTNode *topParent =static_cast<BSTNode *>(this->parent( ));
88
89         // We become left-child of our right-child
90         // newTop takes our place with our parent
91         newTop->setParent( topParent );
92         if( isRightChild && topParent )
93             topParent->setRightChild( newTop );
94         else if( topParent )
95             topParent->setLeftChild( newTop );
96
97         newTop->setRightChild( this );

```



```

98         this->setParent( newTop );
99
100        // We take the left-child of newTop as our right-child
101        this->setLeftChild( newLeft );
102        if( newLeft )
103            newLeft->setParent( this );
104
105        return newTop;
106    }
107
108    bool operator <( const BSTNode<INFO_T> &rhs ) {
109        return S::info() < rhs.info();
110    }
111
112    bool operator <=( const BSTNode<INFO_T> &rhs ) {
113        return S::info() <= rhs.info();
114    }
115
116    bool operator >( const BSTNode<INFO_T> &rhs ) {
117        return S::info() > rhs.info();
118    }
119
120    bool operator >=( const BSTNode<INFO_T> &rhs ) {
121        return S::info() >= rhs.info();
122    }
123    protected:
124        friend class BinarySearchTree<INFO_T>;
125 };
126
127 #endif

```

## 6.9 AVLTree.h

```

1  /**
2   * AVLTree - AVL-SelfOrganizingTree that inherits from SelfOrganizingTree
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file AVLTree.h
7   * @date 9-12-2014
8   */
9
10 #ifndef AVLTREE_H
11 #define AVLTREE_H
12
13 #include "SelfOrganizingTree.h"
14 #include "AVLNode.h"
15
16 template <class INFO_T> class AVLTree : public SelfOrganizingTree<INFO_T> {
17     public:
18         typedef AVLNode<INFO_T> node_t;
19         typedef SelfOrganizingTree<INFO_T> S; // super class
20
21     /**

```

```

22     * @function      AVLTree( )
23     * @abstract      constructor
24     * @post           An AVLTree is created
25     **/
26     AVLTree( ) : S( ) { }
27
28     /**
29     * @function      AVLTree( )
30     * @abstract      constructor
31     * @param         cpy
32     * @post          An AVLTree is created
33     **/
34     AVLTree( const AVLTree& cpy ) : S( cpy ) { }
35
36     /**
37     * @function      insert( )
38     * @abstract      A node with label 'info' is inserted into the tree and
39     *                put in the right place. A label may not appear twice in
40     *                a tree.
41     * @param         info - the label of the node
42     * @return         the node we inserted
43     * @post          The tree now contains a node with 'info'
44     **/
45     node_t* insert( const INFO_T& info,
46                     Tree<INFO_T>* parent =0, // Ignored
47                     bool preferRight =false, // Ignored
48                     int replaceBehavior =0 ) { // Ignored
49         if( S::find( this->root( ), info ) )
50             return 0;
51         node_t *node =new node_t( );
52         S::insertInto( info, node );
53         rebalance( node );
54         return node;
55     }
56
57     /**
58     * @function      remove( )
59     * @abstract      A node is removed in such a way that the properties of
60     *                an AVL tree remain intact.
61     * @param         node - the node we're going to remove
62     * @post          The node has been removed, but the remaining tree still
63     *                contains all of its other nodes and still has all the
64     *                AVL properties.
65     **/
66     void remove( node_t* node ) {
67         // if it's a leaf
68         if( !node->leftChild( ) && !node->rightChild( ) )
69             S::remove( node );
70         // internal node with kids
71         else {
72             if( node->rightChild( ) ) {
73                 node =static_cast<node_t*>( S::replace(
74                     S::min( static_cast<node_t*>(
75                         node->rightChild( ) )->info( ), node ) );

```

```

76         removeMin( static_cast<node_t*>( node->rightChild( ) ) );
77         node->setRightChild( node->rightChild( ) );
78     }
79     else
80         // just delete the node and replace it with its leftChild
81         node->replace( node->leftChild( ) );
82     }
83 }
84
85 private:
86
87 /**
88  * @function      removeMin( )
89  * @abstract      Recursively we go through the tree to find the node with
90  *                the smallest value in the subtree with root node. Then we
91  *                restore the balance factors of all its parents.
92  * @param         node - the root of the subtree we're looking in
93  * @return        At the end of the recursion we return the parent of the
94  *                node with the smallest value. Then we go up the tree and
95  *                rebalance every parent from this upwards.
96  * @post          The node with the smallest value is deleted and every
97  *                node still has the correct balance factor.
98  */
99 node_t* removeMin( node_t* node ) {
100     node_t* temp;
101     if( node->leftChild( ) )
102         temp =removeMin( static_cast<node_t*>( node->leftChild( ) ) );
103     else {
104         temp =static_cast<node_t*>( node->parent( ) );
105         S::remove( node );
106     }
107     rebalance( temp );
108     return temp;
109 }
110
111 /**
112  * @function      removeMax( )
113  * @abstract      Recursively we go through the tree to find the node with
114  *                the highest value in the subtree with root node. Then we
115  *                restore the balance factors of all its parents.
116  * @param         node - the root of the subtree we're looking in
117  * @return        At the end of the recursion we return the parent of the
118  *                node with the highest value. Then we go up the tree and
119  *                rebalance every parent from this upwards.
120  * @post          The node with the highest value is deleted and every
121  *                node still has the correct balance factor.
122  */
123 node_t* removeMax( node_t* node ) {
124     node_t* temp;
125     if( node->rightChild( ) )
126         temp =removeMin( static_cast<node_t*>( node->rightChild( ) ) );
127     else {
128         temp =static_cast<node_t*>( node->parent( ) );
129         S::remove( node );

```

```

130     }
131     rebalance( temp );
132     return temp;
133 }
134
135 /**
136  * @function      rotateLeft( )
137  * @abstract      We rotate a node left and make sure all the internal
138  *                heights of the nodes are up to date.
139  * @param          node - the node we're going to rotate left
140  * @return         we return the node that is now at the top of this
141  *                particular subtree.
142  * @post           The node is rotated to the left and the heights are up
143  *                to date.
144  */
145 node_t* rotateLeft( node_t* node ) {
146     node_t *temp =static_cast<node_t*>( S::rotateLeft( node ) );
147     temp->updateHeight( );
148     if( temp->leftChild( ) )
149         static_cast<node_t*>( temp->leftChild( ) )->updateHeight( );
150     return temp;
151 }
152
153 /**
154  * @function      rotateRight( )
155  * @abstract      We rotate a node right and make sure all the internal
156  *                heights of the nodes are up to date.
157  * @param          node - the node we're going to rotate right
158  * @return         we return the node that is now at the top of this
159  *                particular subtree.
160  * @post           The node is rotated to the right and the heights are up
161  *                to date.
162  */
163 node_t* rotateRight( node_t* node ) {
164     node_t* temp =static_cast<node_t*>( S::rotateRight( node ) );
165     temp->updateHeight( );
166     if( temp->rightChild( ) )
167         static_cast<node_t*>( temp->rightChild( ) )->updateHeight( );
168     return temp;
169 }
170
171 /**
172  * @function      rebalance( )
173  * @abstract      The tree is rebalanced. We do the necessary rotations
174  *                from the bottom up to make sure the AVL properties are
175  *                still intact.
176  * @param          node - the node we're going to rebalance
177  * @post           The tree is now perfectly balanced.
178  */
179 void rebalance( node_t* node ) {
180     node->updateHeight( );
181
182     node_t* temp =node;
183     while( temp->parent( ) ) {

```

```

184         temp =static_cast<node_t*>( temp->parent( ) );
185         temp->updateHeight( );
186         // right subtree too deep
187         if( temp->balanceFactor( ) == 2 ) {
188             if( temp->rightChild( ) ) {
189                 if( static_cast<node_t*>( temp->rightChild( ) )
190                     ->balanceFactor( ) < 0 )
191                     this->rotateRight(
192                         static_cast<node_t*>( temp->rightChild( ) ) );
193             }
194             this->rotateLeft( temp );
195         }
196         // left subtree too deep
197         else if( temp->balanceFactor( ) == -2 ) {
198             if( temp->leftChild( ) ) {
199                 if( static_cast<node_t*>( temp->leftChild( ) )->
200                     balanceFactor( ) > 0 )
201                     this->rotateLeft(
202                         static_cast<node_t*>( temp->leftChild( ) ) );
203             }
204             this->rotateRight( temp );
205         }
206     }
207 };
208
209
210 #endif

```

## 6.10 AVLNode.h

```

1  /**
2   * AVLNode - Node atom type for AVLTree
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file AVLNode.h
7   * @date 9-11-2014
8   */
9
10 #ifndef AVLNODE_H
11 #define AVLNODE_H
12
13 #include "BSTNode.h"
14
15 template <class INFO_T> class AVLTree;
16
17 template <class INFO_T> class AVLNode : public BSTNode<INFO_T>
18 {
19     public:
20         typedef BSTNode<INFO_T> S; // super class
21
22         /**
23          * @function AVLNode( )
24          * @abstract Constructor, creates a node

```

```

25     * @param      info, the contents of a node
26     * @param      parent, the parent of the node
27     * @post       A node has been created.
28     **/
29     AVLNode( const INFO_T& info, AVLNode<INFO_T>* parent =0 )
30         : S( info, parent ) {
31     }
32
33     /**
34     * @function     AVLNode( )
35     * @abstract     Constructor, creates a node
36     * @param      parent, the parent of the node
37     * @post       A node has been created.
38     **/
39     AVLNode( AVLNode<INFO_T>* parent =0 )
40         : S( (S)parent ) {
41     }
42
43     /**
44     * @function     balanceFactor( )
45     * @abstract     we return the height of the rightchild subtracted with
46     *               the height of the left child. Because of the properties
47     *               of an AVLtree, this should never be less than -1 or more
48     *               than 1.
49     * @return      we return the difference between the height of the
50     *               rightchild and the leftchild.
51     * @post       The difference between the two child nodes is returned.
52     **/
53     int balanceFactor( ){
54         return static_cast<AVLNode *>( this->rightChild( ) )->getHeight( ) -
55                static_cast<AVLNode *>( this->leftChild( ) )->getHeight( );
56     }
57
58     /**
59     * @function     updateHeight( )
60     * @abstract     we update the height of the node.
61     * @pre          The children of the node need to have the correct height.
62     * @post       The node now has the right height.
63     **/
64     void updateHeight( ) {
65         int lHeight =static_cast<AVLNode *>( this->leftChild( ) )
66                     ->getHeight( );
67         int rHeight =static_cast<AVLNode *>( this->rightChild( ) )
68                     ->getHeight( );
69
70         this->height =( 1 + ( ( lHeight > rHeight ) ? lHeight : rHeight ) );
71     }
72
73     /**
74     * @function     getHeight( )
75     * @abstract     we want to know the height of the node.
76     * @return      we return the height of the node.
77     * @post       The current height of the node is returned.
78     **/

```

```

79         int getHeight( ) {
80             return (this ? this->height : 0);
81         }
82
83         bool operator <( const AVLNode<INFO_T> &rhs ) {
84             return S::info() < rhs.info();
85         }
86
87         bool operator <=( const AVLNode<INFO_T> &rhs ) {
88             return S::info() <= rhs.info();
89         }
90
91         bool operator >( const AVLNode<INFO_T> &rhs ) {
92             return S::info() > rhs.info();
93         }
94
95         bool operator >=( const AVLNode<INFO_T> &rhs ) {
96             return S::info() >= rhs.info();
97         }
98
99     protected:
100         friend class AVLTree<INFO_T>;
101
102     private:
103         int height;
104 };
105
106
107 #endif

```

## 6.11 SplayTree.h

```

1  /**
2   * SplayTree - Splay-tree implementation
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file SplayTree.h
7   * @date 3-11-2014
8   */
9
10 #ifndef SPLAYTREE_H
11 #define SPLAYTREE_H
12
13 #include "SelfOrganizingTree.h"
14
15 template <class INFO_T> class SplayTree : public SelfOrganizingTree<INFO_T> {
16     public:
17         typedef BSTNode<INFO_T> node_t;
18         typedef SelfOrganizingTree<INFO_T> S; // super class
19
20         SplayTree( ) : SelfOrganizingTree<INFO_T>( ) { }
21
22         SplayTree( const SplayTree& copy )

```

```

23         : SelfOrganizingTree<INFO_T>( copy ) { }
24
25     /**
26     * @function    insert( )
27     * @abstract    reimplemented virtual function from BinarySearchTree<>
28     *              the new node will always be the root
29     * @param       info, the contents of the new node
30     * @param       parent, ignored
31     * @param       preferRight, ignored
32     * @param       replaceBehavior, ignored
33     * @return      returns a pointer to the inserted node (root)
34     */
35     virtual node_t* insert( const INFO_T& info,
36                           TreeNode<INFO_T>* parent =0, // Ignored
37                           bool preferRight =false, // Ignored
38                           int replaceBehavior =0 ) { // Ignored
39         return splay( S::insert( info, parent, preferRight ) );
40     }
41
42     /**
43     * @function    replace( )
44     * @abstract    reimplemented virtual function from BinarySearchTree<>
45     *              replaces a given node or the root
46     *              the resulting node will be propagated to location of the root
47     * @param       info, the contents of the new node
48     * @param       node, node to be replaced
49     * @param       alignRight, ignored
50     * @param       replaceBehavior, ignored
51     * @return      returns a pointer to the new node (=root)
52     * @pre         node should be in this tree
53     * @post        replace() will delete and/or remove node.
54     *              if node is 0, it will take the root instead
55     */
56     virtual node_t* replace( const INFO_T& info,
57                             TreeNode<INFO_T>* node =0,
58                             bool alignRight =false,
59                             int replaceBehavior =0 ) {
60         return splay( S::replace( info, node, alignRight ) );
61     }
62
63     /**
64     * @function    remove( )
65     * @abstract    reimplemented virtual function from BinarySearchTree<>
66     *              removes a given node or the root and restores the
67     *              BST properties. The node-to-be-removed will be spayed
68     *              before removal.
69     * @param       node, node to be removed
70     * @pre         node should be in this tree
71     * @post        memory for node will be deallocated
72     */
73     virtual void remove( TreeNode<INFO_T> *node ) {
74         S::remove( splay( static_cast<node_t*>(node) ) );
75     }
76

```



```

77      /**
78      * @function   find( )
79      * @abstract   reimplemented virtual function from Tree<>
80      *             performs a binary search in a given (sub)tree
81      *             splays the node (if found) afterwards
82      * @param      haystack, the subtree to search. Give 0 for the entire tree
83      * @param      needle, key/info-value to find
84      * @return     returns a pointer to node, if found
85      * @pre        haystack should be in this tree
86      * @post       may return 0, the structure of the tree may change
87      */
88      virtual TreeNode<INFO_T>* find( TreeNode<INFO_T>* haystack,
89                                     const INFO_T& needle ) {
90          return splay( static_cast<node_t*>( S::find( haystack, needle ) ) );
91      }
92
93      /**
94      * @function   splay( )
95      * @abstract   Performs the splay operation on a given node.
96      *             'Splay' means a certain amount of rotations in order
97      *             to make the given node be the root of the tree while
98      *             maintaining the binary search tree properties.
99      * @param      node, the node to splay
100     * @pre        The node must be a node in this tree
101     * @post       The node will be the new root of the tree
102     *             No nodes will be invalidated and no new memory is
103     *             allocated. Iterators may become invalid.
104     */
105     node_t* splay( node_t* node ) {
106
107         enum MODE {
108             LEFT =0x1, RIGHT =0x2,
109             PLEFT =0x4, PRIGHT =0x8 };
110
111         // Can't splay the root (or null)
112         if( !node || S::m_root == node )
113             return node;
114
115         node_t *p =static_cast<node_t*>( node->parent( ) );
116         int mode;
117
118         while( p != S::m_root ) {
119             if( p->leftChild( ) == node )
120                 mode =RIGHT;
121             else
122                 mode =LEFT;
123
124             assert( p->parent( ) != nullptr );
125
126             // Node's grandparent
127             node_t* g =static_cast<node_t*>( p->parent( ) );
128
129             if( g->leftChild( ) == p )
130                 mode |= PRIGHT;

```

```

131         else
132             mode |= PLEFT;
133
134         // True if either mode is LEFT|PLEFT or RIGHT|PRIGHT
135         if( (mode >> 2) == (mode & 0x3 ) ) {
136             // the 'zig-zig' step
137             // first rotate g-p then p-node
138
139             if( mode & PLEFT )
140                 this->rotateLeft( g );
141             else
142                 this->rotateRight( g );
143
144             if( mode & LEFT )
145                 this->rotateLeft( p );
146             else
147                 this->rotateRight( p );
148         }
149         else {
150             // the 'zig-zag' step
151             // first rotate p-node then g-p
152
153             if( mode & LEFT )
154                 this->rotateLeft( p );
155             else
156                 this->rotateRight( p );
157
158             if( mode & PLEFT )
159                 this->rotateLeft( g );
160             else
161                 this->rotateRight( g );
162         }
163
164         // perhaps we're done already...
165         if( node == this->root( ) )
166             return node;
167         else
168             p =static_cast<node_t*>( node->parent( ) );
169     }
170
171     // The 'zig-step': parent of node is the root
172
173     if( p->leftChild( ) == node )
174         this->rotateRight( p );
175     else
176         this->rotateLeft( p );
177
178     return node;
179 }
180 };
181
182 #endif

```

## 6.12 Treap.h

```

1  /**
2   * Treap - Treap that inherits from SelfOrganizingTree
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file Treap.h
7   * @date 9-12-2014
8   */
9
10 #ifndef TREAP_H
11 #define TREAP_H
12
13 #include "SelfOrganizingTree.h"
14 #include "TreapNode.h"
15
16 template <class INFO_T> class Treap : public SelfOrganizingTree<INFO_T> {
17     public:
18         typedef TreapNode<INFO_T> node_t;
19         typedef SelfOrganizingTree<INFO_T> S; // super class
20
21         /**
22          * @function Treap( )
23          * @abstract constructor
24          * @post A Treap is created
25          */
26         Treap( int randomRange =100 ) : S( ) {
27             random =randomRange;
28             srand( time( NULL ) );
29         }
30
31         /**
32          * @function Treap( )
33          * @abstract constructor
34          * @param cpy
35          * @post A Treap is created
36          */
37         Treap( const Treap& cpy, int randomRange =100 ) : S( cpy ) {
38             random =randomRange;
39             srand( time( NULL ) );
40         }
41
42         /**
43          * @function insert( )
44          * @abstract A node with label 'info' is inserted into the tree and
45          * put in the right place. A label may not appear twice in
46          * a tree.
47          * @param info - the label of the node
48          * @return the node we inserted
49          * @post The tree now contains a node with 'info'
50          */
51         node_t* insert( const INFO_T& info,
52                         TreeNode<INFO_T>* parent =0, // Ignored
53                         bool preferRight =false, // Ignored
54                         int replaceBehavior =0 ) { // Ignored

```

```

55         // Prevent duplicates
56
57         if( S::find( this->root( ), info ) )
58             return 0;
59         node_t *node = new node_t( );
60         S::insertInto( info, node );
61         node->priority = rand( ) % random + 1;
62         rebalance( node );
63
64         return node;
65     }
66
67 /**
68  * @function      remove( )
69  * @abstract      the node provided with the parameter is deleted from the
70  *                tree by rotating it down until it becomes a leaf or has
71  *                only one child. In the first case it's just deleted,
72  *                in the second it's replaced by its subtree.
73  * @param         node - the node to be deleted
74  * @post          The node is deleted from the tree which still retains
75  *                the Treap properties.
76  */
77 void remove( node_t* node ) {
78     node_t *temp = node;
79     // rotating it down until the condition no longer applies.
80     while( temp->leftChild( ) && temp->rightChild( ) )
81     {
82         if( static_cast<node_t*>( temp->rightChild( ) )->priority >
83             static_cast<node_t*>( temp->leftChild( ) )->priority )
84             this->rotateLeft( temp );
85         else
86             this->rotateRight( temp );
87     }
88     // if it's a leaf
89     if( !temp->leftChild( ) && !temp->rightChild( ) )
90         S::remove( temp );
91     // if it only has a right child
92     else if( !temp->leftChild( ) )
93         temp->replace( static_cast<node_t*>( temp->rightChild( ) ) );
94     // if it only has a left child
95     else if( !temp->rightChild( ) )
96         temp->replace( static_cast<node_t*>( temp->leftChild( ) ) );
97 }
98
99 private:
100     int random;
101
102 /**
103  * @function      rebalance( )
104  * @abstract      The tree is rebalanced. We do the necessary rotations
105  *                from the bottom up to make sure the Treap properties are
106  *                still intact.
107  * @param         info - the label of the node
108  * @return        the node we inserted

```

```

109      * @post          The tree is now perfectly balanced.
110      **/
111      void rebalance( node_t* node ) {
112          if( !node )
113              return;
114          node_t* temp =node;
115          int myPriority =node->priority;
116          while( temp->parent( ) &&
117              myPriority >
118                  static_cast<node_t*>( temp->parent( ) )->priority ) {
119              temp =static_cast<node_t*>( temp->parent( ) );
120              if( temp->leftChild( ) == node )
121                  this->rotateRight( temp );
122              else
123                  this->rotateLeft( temp );
124          }
125      }
126
127 };
128
129 #endif

```

### 6.13 TreapNode.h

```

1  /**
2   * TreapNode - Node atom type for Treap
3   *
4   * @author Micky Faas (s1407937)
5   * @author Lisette de Schipper (s1396250)
6   * @file TreapNode.h
7   * @date 9-11-2014
8   **/
9
10 #ifndef TREAPNODE.H
11 #define TREAPNODE.H
12
13 #include "BSTNode.h"
14
15 template <class INFO_T> class Treap;
16
17 template <class INFO_T> class TreapNode : public BSTNode<INFO_T>
18 {
19     public:
20         typedef BSTNode<INFO_T> S; // super class
21
22         /**
23          * @function TreapNode( )
24          * @abstract Constructor, creates a node
25          * @param info, the contents of a node
26          * @param parent, the parent of the node
27          * @post A node has been created.
28          **/
29         TreapNode( const INFO_T& info, TreapNode<INFO_T>* parent =0 )
30             : S( info, parent ), priority( 0 ) {

```

```

31     }
32
33     /**
34     * @function      TreapNode( )
35     * @abstract      Constructor, creates a node
36     * @param         parent, the parent of the node
37     * @post          A node has been created.
38     */
39     TreapNode( TreapNode<INFO_T>* parent =0 )
40         : S( (S)parent ), priority( 0 ) {
41     }
42
43     /**
44     * @function      replace( )
45     * @abstract      Replaces the node with another node in the tree
46     * @param         n, the node we replace the node with, this one gets deleted
47     * @pre           both this node and n must be in the same parent tree
48     * @post          The node will be replaced and n will be deleted.
49     */
50     void replace( TreapNode<INFO_T>* n ) {
51         priority = n->priority;
52         this->S::replace( n );
53     }
54
55     bool operator <( const TreapNode<INFO_T> &rhs ) {
56         return S::info() < rhs.info();
57     }
58
59     bool operator <=( const TreapNode<INFO_T> &rhs ) {
60         return S::info() <= rhs.info();
61     }
62
63     bool operator >( const TreapNode<INFO_T> &rhs ) {
64         return S::info() > rhs.info();
65     }
66
67     bool operator >=( const TreapNode<INFO_T> &rhs ) {
68         return S::info() >= rhs.info();
69     }
70
71     int priority;
72
73     protected:
74         friend class Treap<INFO_T>;
75 };
76
77
78 #endif

```