

Chapter 8

AVL Search Trees

Objectives

Upon completion you will be able to:

- Explain the differences between a BST and an AVL tree
- Insert, delete, and process nodes in an AVL tree
- Understand the operation of the AVL tree ADT
- Write application programs using an AVL tree

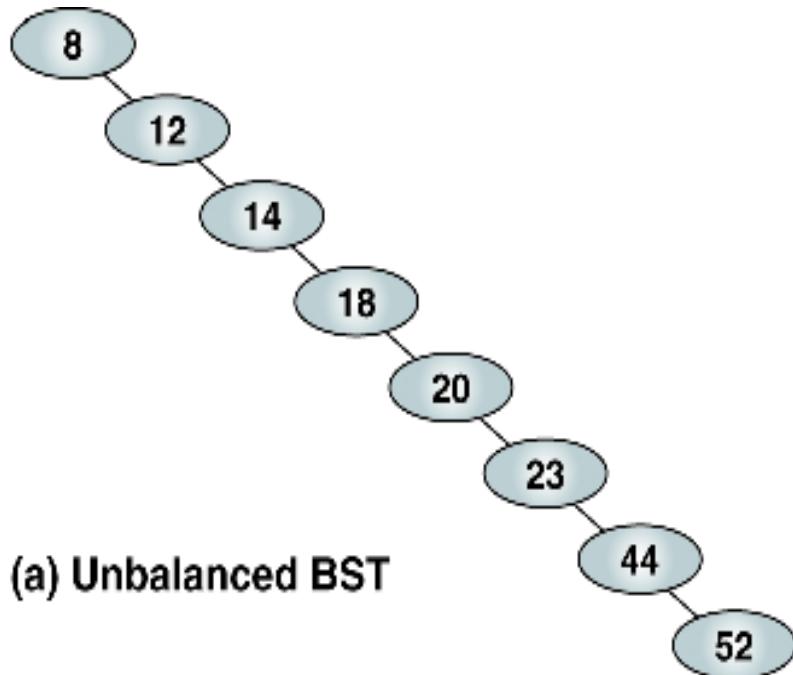
8-1 AVL Tree Basic Concepts

An AVL (Adelson-Velskii and Landis) tree is a BST that is guaranteed to always be balanced. We begin with a discussion of its basic structural differences and then discuss the four different balancing situations that can occur when data are inserted or deleted.

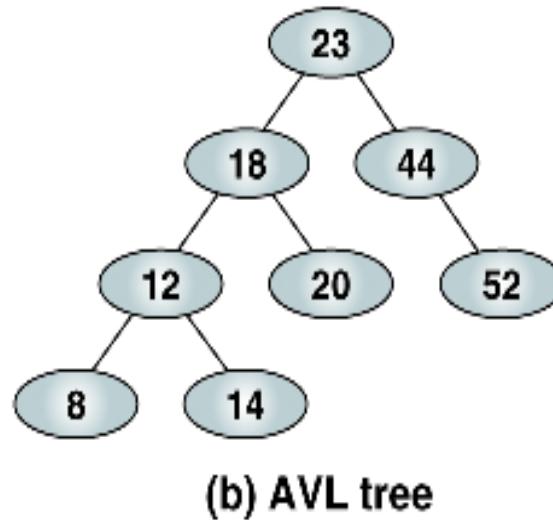
AVL tree = BST + balancing

- **AVL Tree Balance Factor**
- **Balancing Trees**

Two Binary Trees



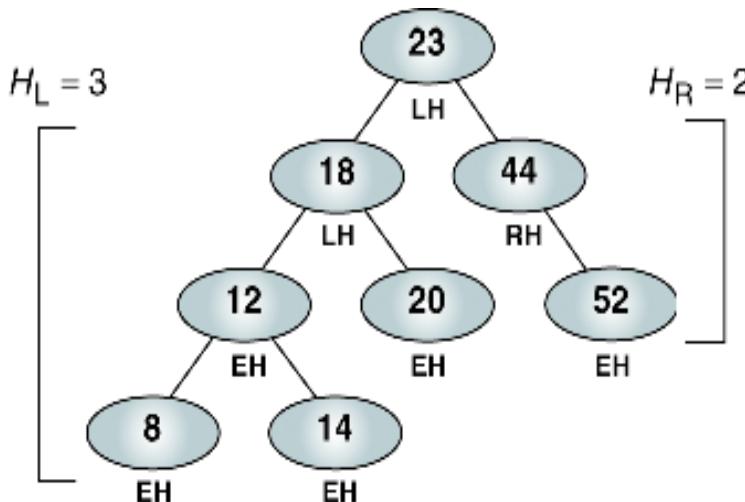
(a) Unbalanced BST



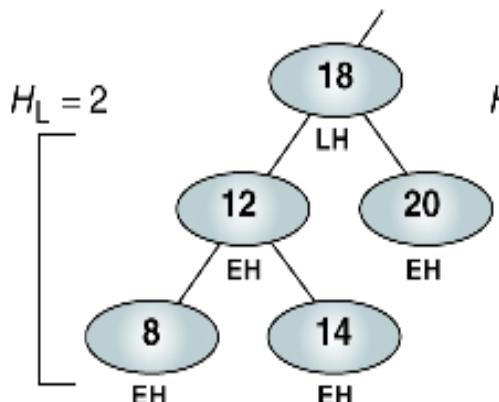
(b) AVL tree

AVL Tree

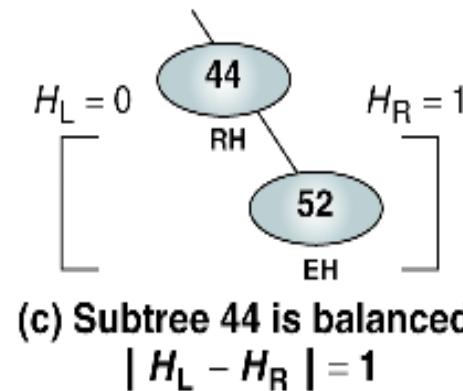
LH: left high (+1)
EH: even high (0)
RH: right high (-1)



(a) Tree 23 appears balanced: $H_L - H_R = 1$

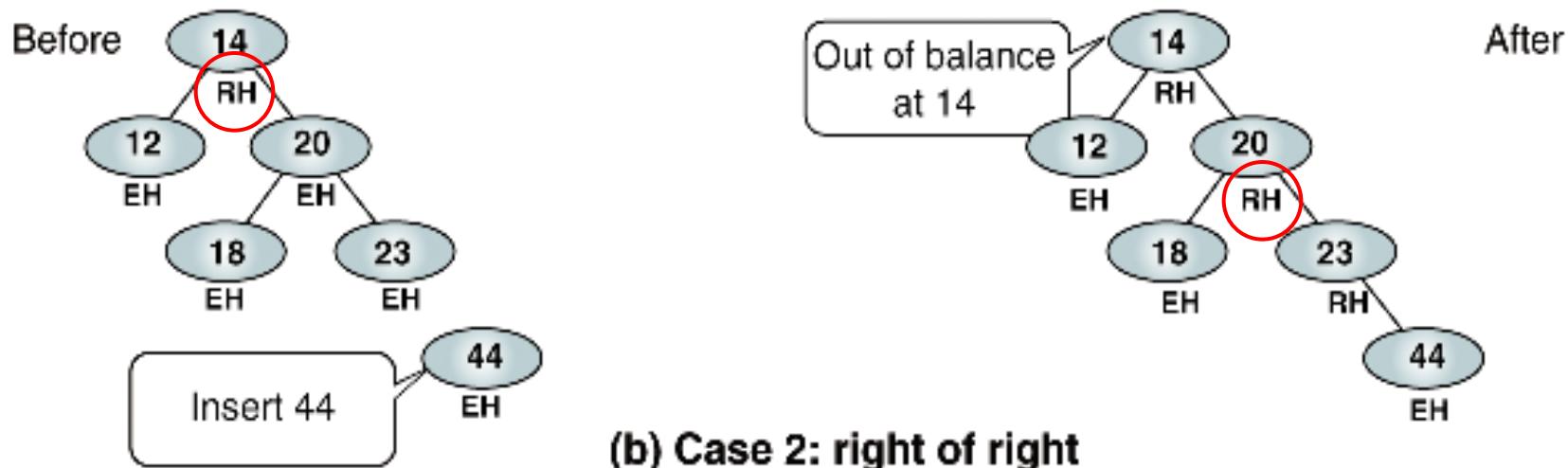
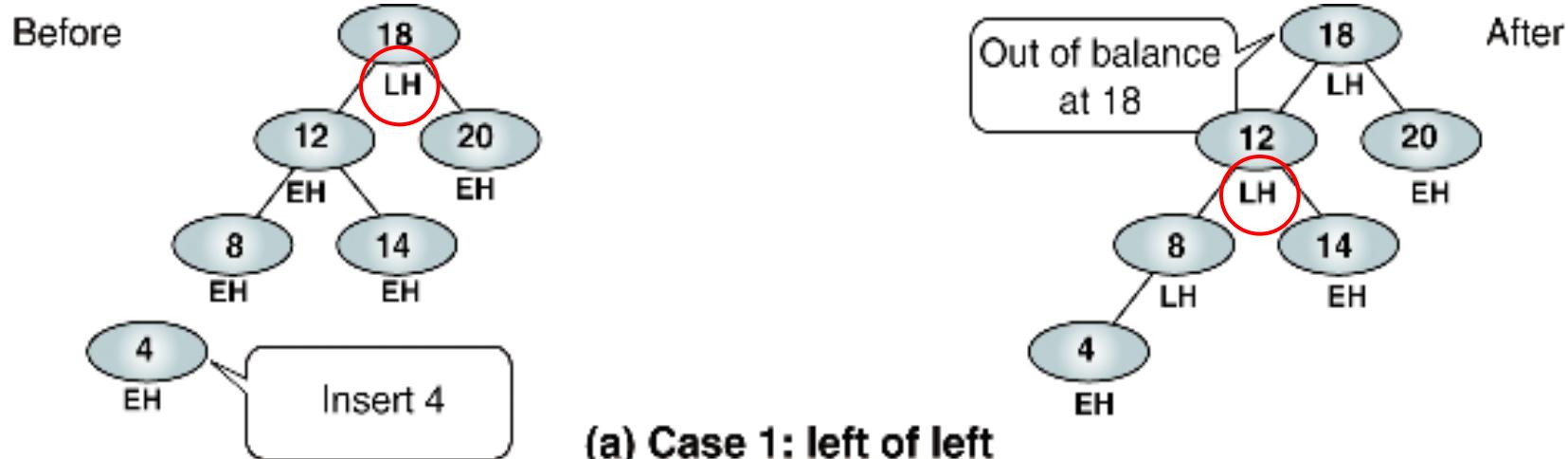


(b) Subtree 18 appears balanced:
 $H_L - H_R = 1$

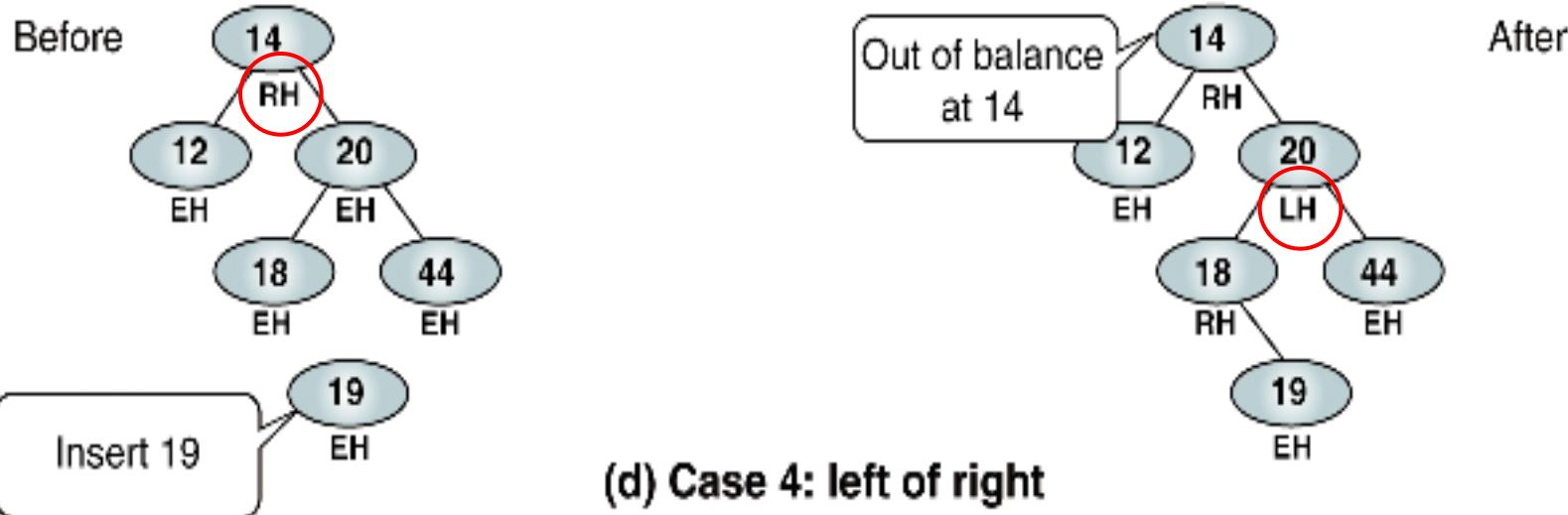
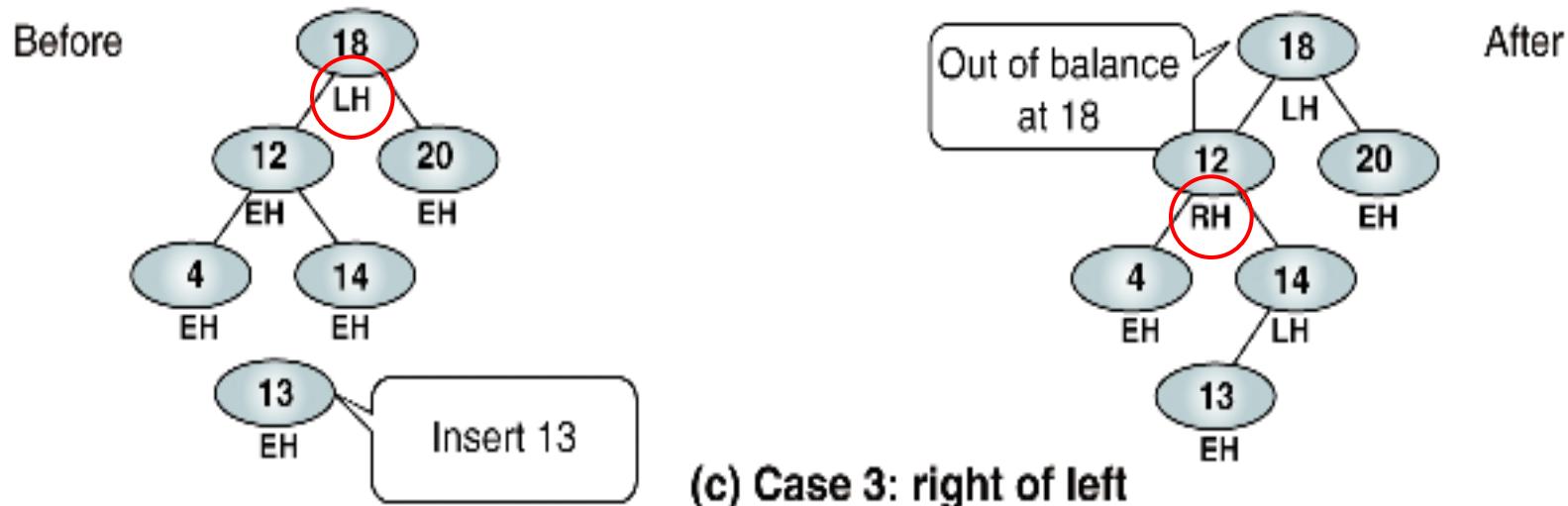


(c) Subtree 44 is balanced:
 $| H_L - H_R | = 1$

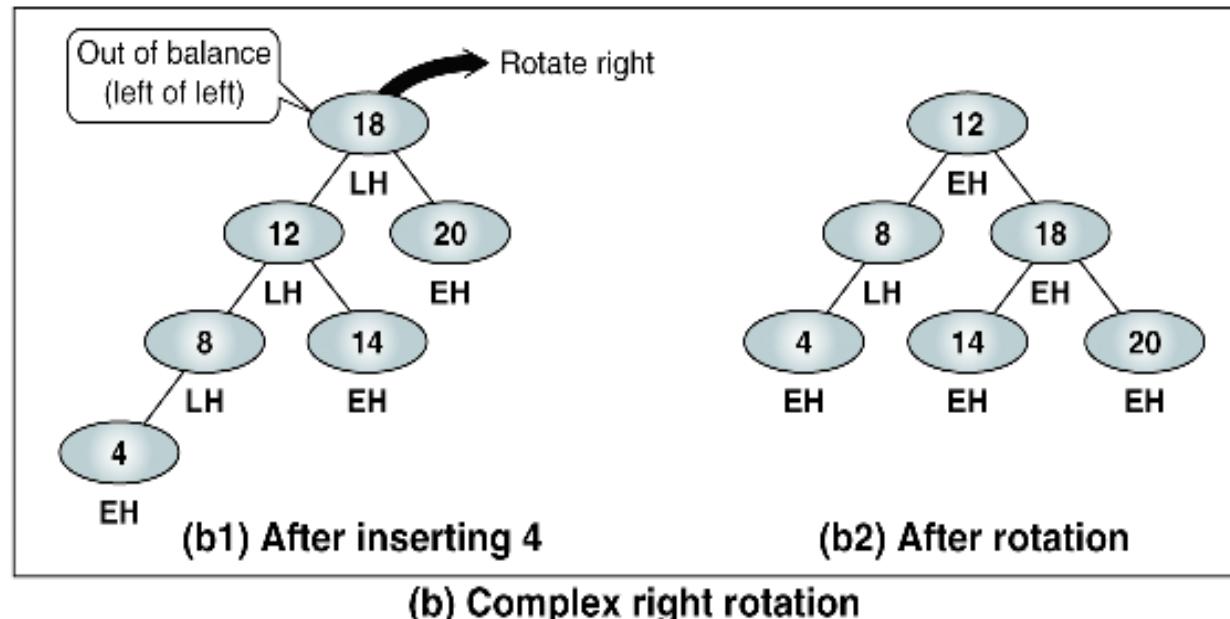
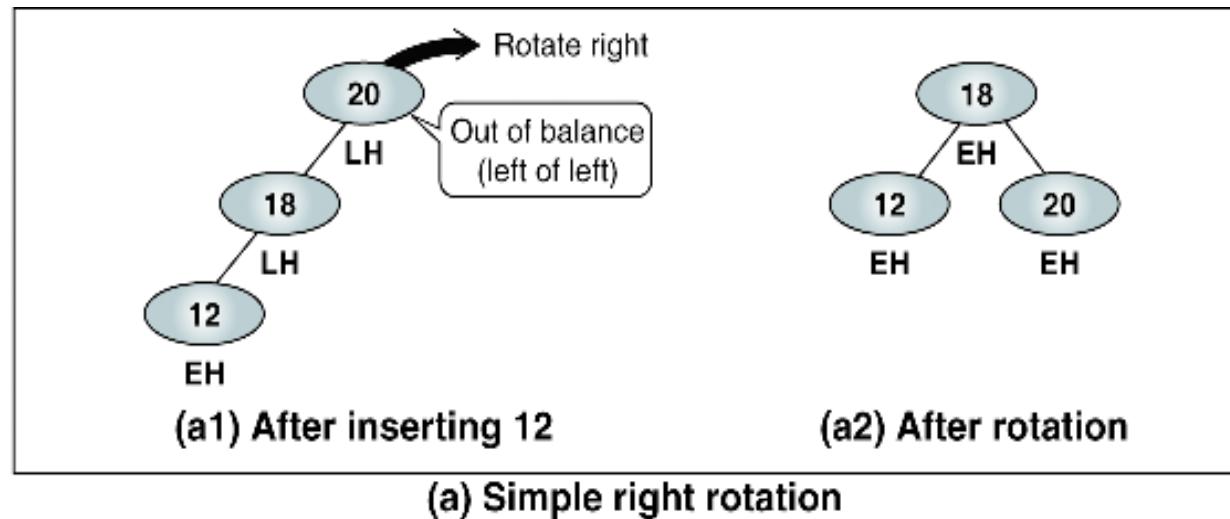
Out-of-balance AVL Tree



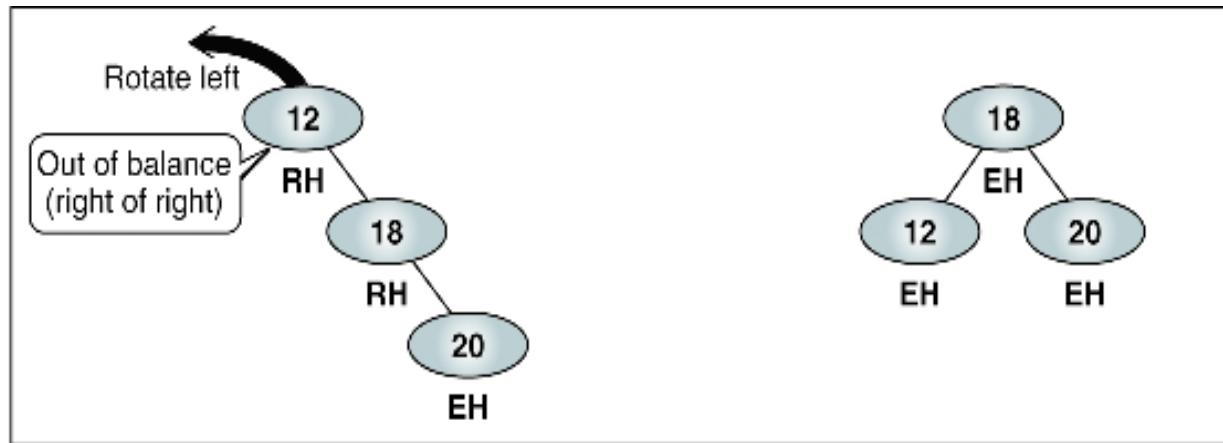
Out-of-balance AVL Tree (cont.)



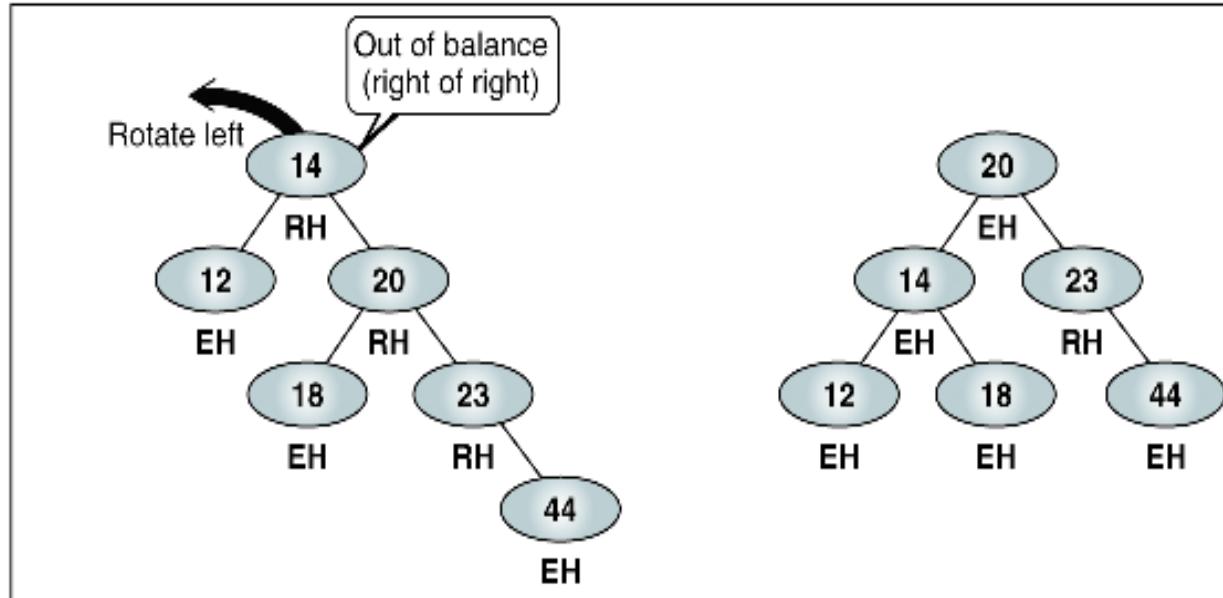
Left of Left – Single Rotation Right



Right of Right – Single Rotation Left

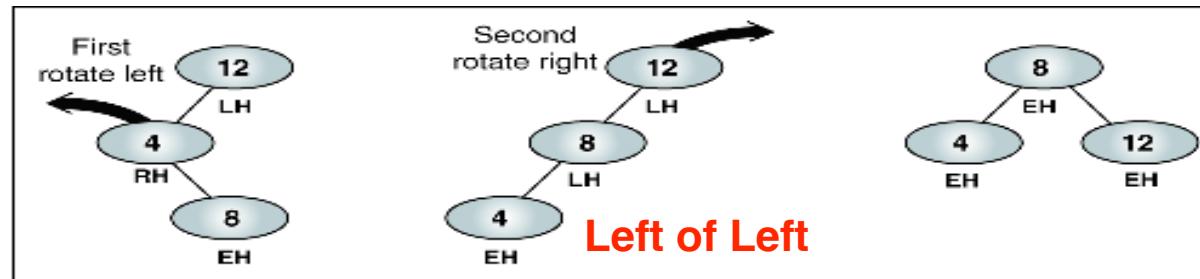


(a) Simple left rotation

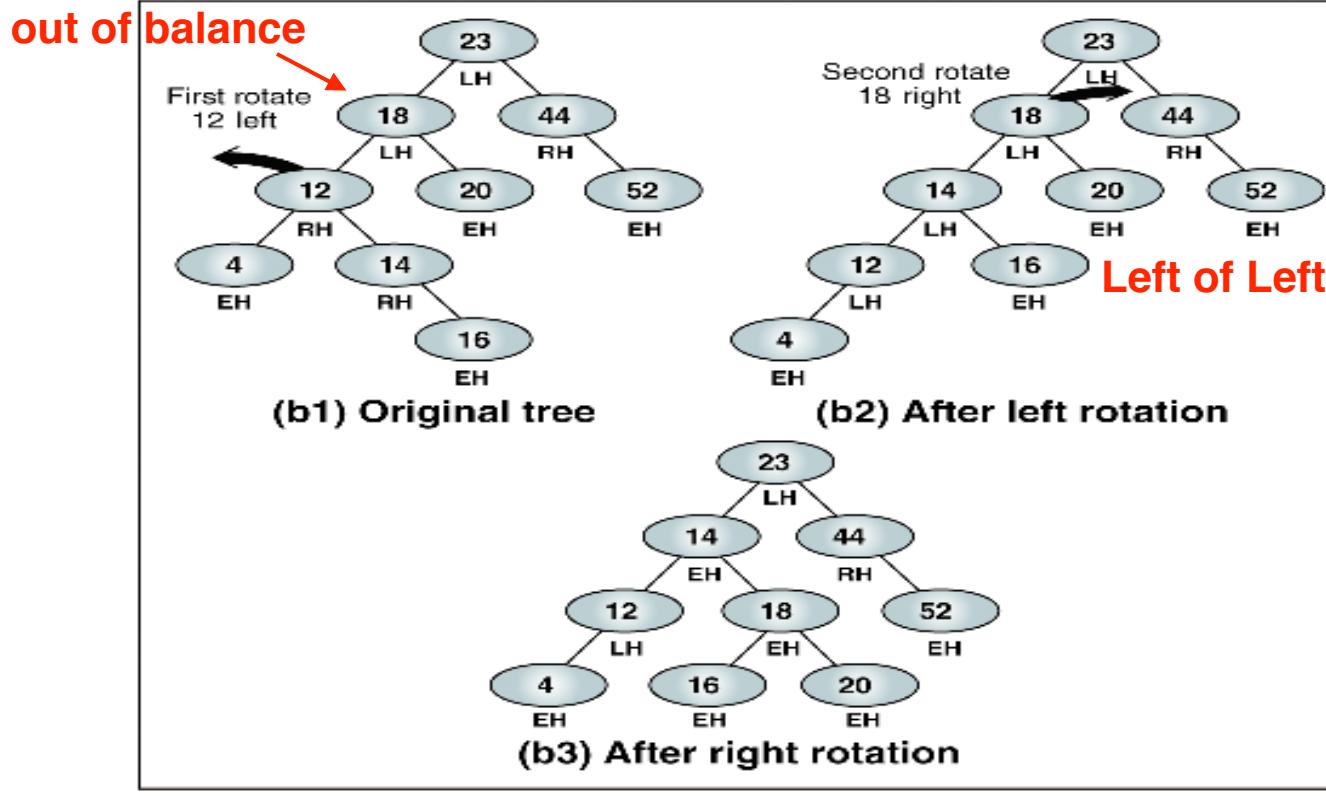


(b) Complex left rotation

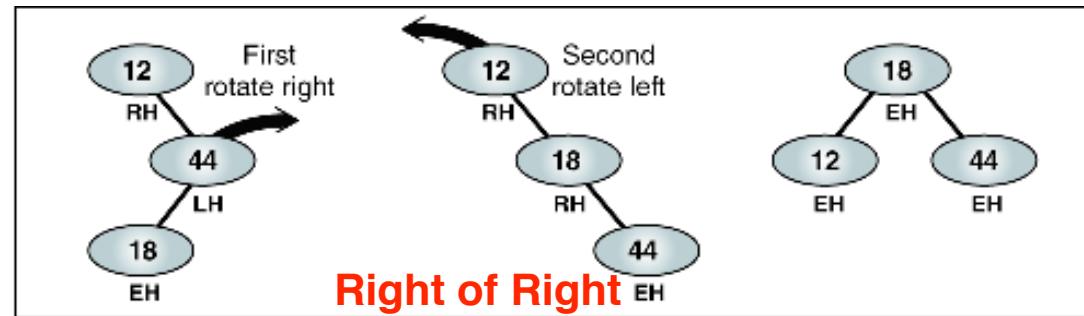
Right of Left – Double Rotation Right



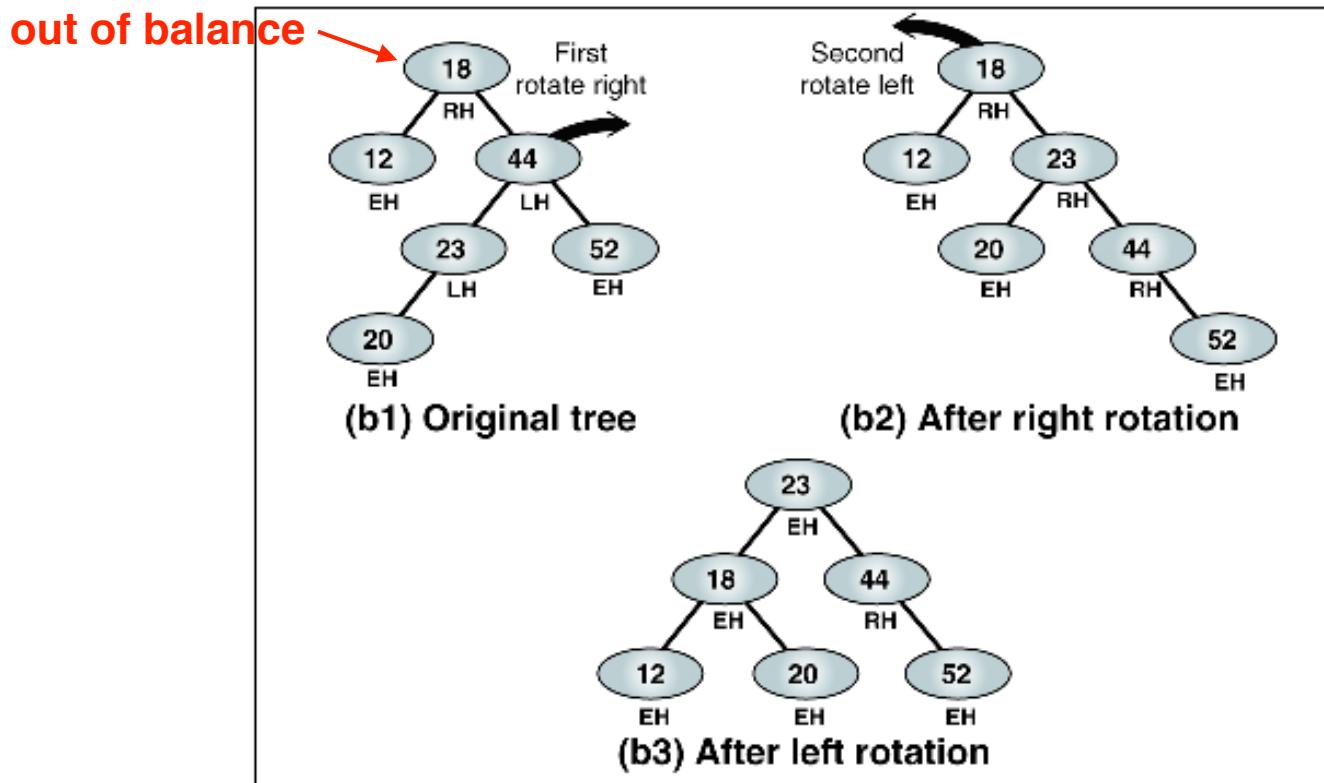
(a) Simple double rotation right



Left of Right – Double Rotation Right



(a) Simple double rotation right



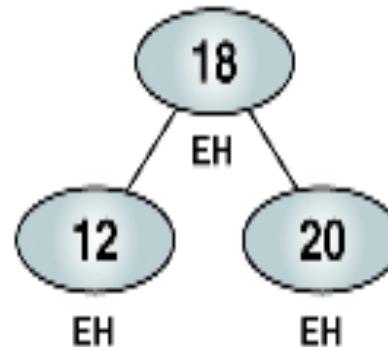
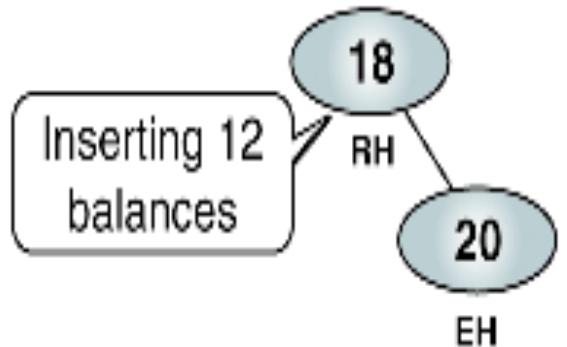
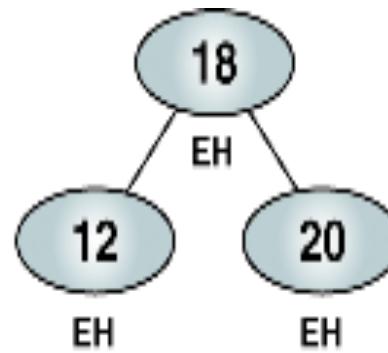
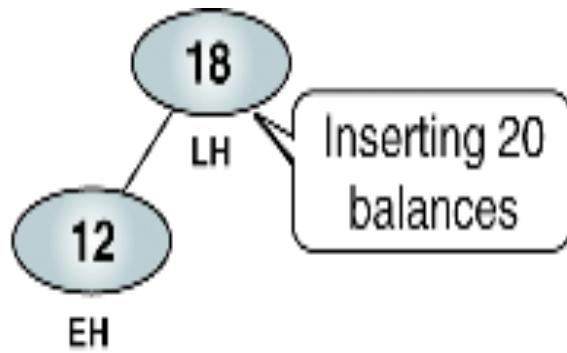
(b) Complex double rotation right

8-2 AVL Tree Implementations

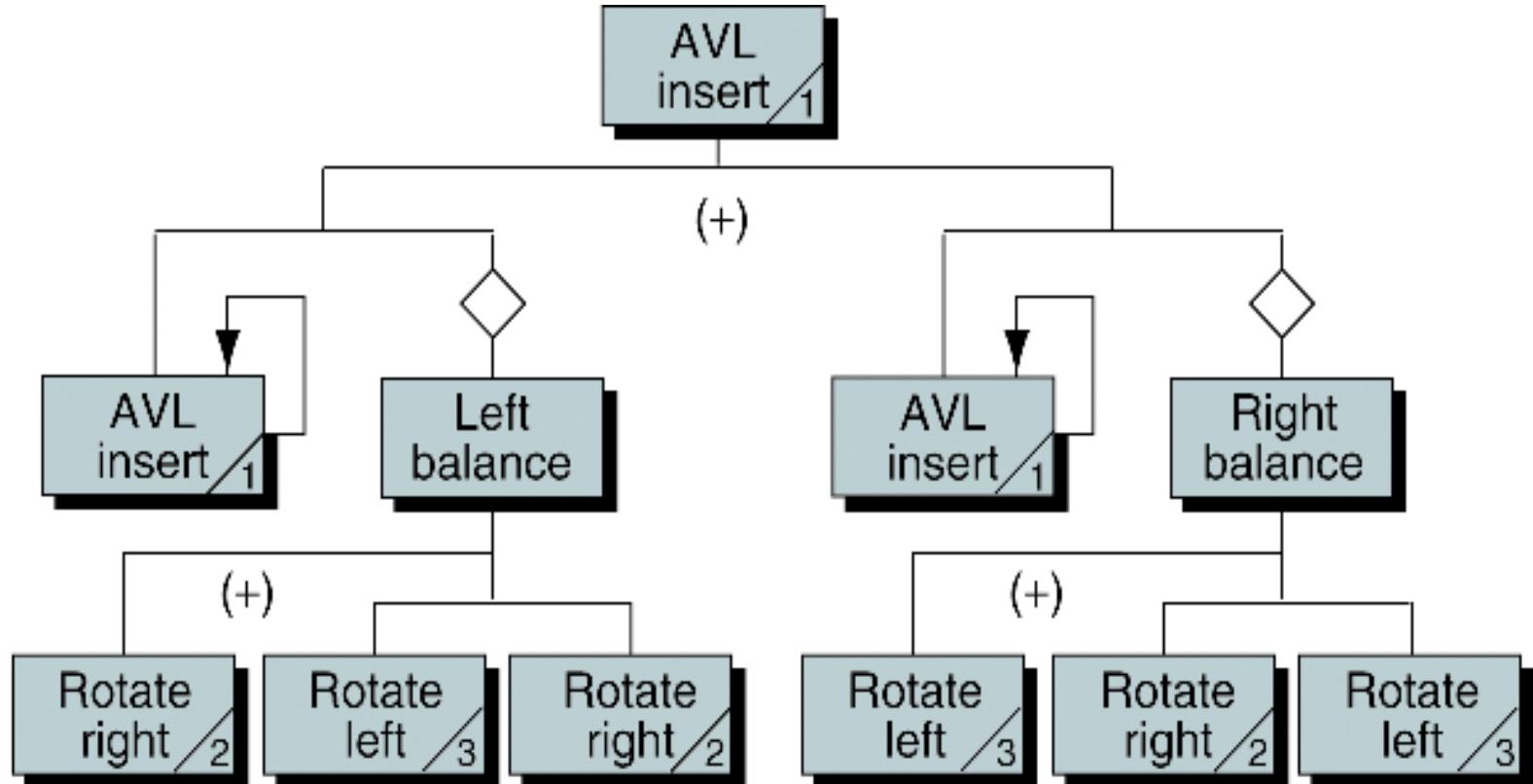
Insertion and deletion in an AVL tree follow the same basic rules for insertion and deletion in a BST. The difference lies in the tree balancing, which occurs as we back out of the tree. In this section we develop the insertion and deletion algorithms for a AVL tree, including algorithms to balance the tree.

- Insert into AVL Tree
- AVL Tree Delete Algorithm

Automatic AVL Tree Balancing



AVL Tree Insert Design



AVL Tree Insert

```
Algorithm AVLInsert (root, newData)
Using recursion, insert a node into an AVL tree.
    Pre    root is pointer to first node in AVL tree/subtree
           newData is pointer to new node to be inserted
    Post   new node has been inserted
    Return root returned recursively up the tree
1 if (subtree empty)
    Insert at root
    1 insert newData at root
    2 return root
2 end if
3 if (newData < root)
    1 AVLInsert (left subtree, newData)
    2 if (left subtree taller)
        1 leftBalance (root)
    3 end if
4 else
    New data >= root data
    1 AVLInsert (right subtree, newPrt)
    2 if(right subtree taller)
        1 rightBalance (root)
    3 end if
5 end if
6 return root
end AVLInsert
```

AVL Tree Left Balance

```
Algorithm leftBalance (root)
```

This algorithm is entered when the root is left high (the left subtree is higher than the right subtree).

Pre root is a pointer to the root of the [sub]tree

Post root has been updated (if necessary)

```
1 if (left subtree high)
    1 rotateRight (root)
2 else
    1 rotateLeft (left subtree)
    2 rotateRight (root)
3 end if
end leftBalance
```

AVL Tree Rotate Right A diagram of an AVL tree at its initial state. The root node is labeled '20'. It has a left child '18' and a right child '12'. Node '18' has two children: '12' (left) and '19' (right). A blue arrow labeled 'root' points to node '20'. Another blue arrow labeled 'To parent' points from node '12' up to node '18'. A curved arrow labeled 'Rotate right' points from node '18' to node '20'. (a) At beginning A diagram showing the state of the AVL tree after a left-right double rotation. The root node is now '20'. It has a left child '18' and a right child '19'. Node '18' has two children: '12' (left) and '20' (right). A blue arrow labeled 'root' points to node '20'. Another blue arrow labeled 'To parent' points from node '12' up to node '18'. A curved arrow labeled 'Rotate right' points from node '18' to node '20'. (b) After exchange A diagram showing the state of the AVL tree after it has been attached back to the original root. The root node is '20'. It has a left child '18' and a right child '12'. Node '18' has two children: '12' (left) and '20' (right). Node '20' has a right child '19'. A blue arrow labeled 'root' points to node '20'. Another blue arrow labeled 'To parent' points from node '12' up to node '18'. A curved arrow labeled 'Rotate right' points from node '18' to node '20'. (c) After attaching root A diagram showing the final balanced state of the AVL tree. The root node is '18'. It has a left child '12' and a right child '20'. Node '12' has a right child '19'. A blue arrow labeled 'root' points to node '18'. (d) At end 16

Rotate AVL Tree Right and Left

```
Algorithm rotateRight (root)
```

This algorithm exchanges pointers to rotate the tree right.

Pre root points to tree to be rotated

Post node rotated and root updated

- 1 exchange left subtree with right subtree of left subtree

- 2 make left subtree new root

end rotateRight

```
Algorithm rotateLeft (root)
```

This algorithm exchanges pointers to rotate the tree left.

Pre root points to tree to be rotated

Post node rotated and root updated

- 1 exchange right subtree with left subtree of right subtree

- 2 make right subtree new root

end rotateLeft

AVL Tree Delete

```
Algorithm AVLDelete (root, dltKey, success)
This algorithm deletes a node from an AVL tree and
rebalances if necessary.

Pre    root is a pointer to a [sub]tree
       dltKey is the key of node to be deleted
       success is reference to boolean variable

Post   node deleted if found, tree unchanged if not
       success set true (key found and deleted)
              or false (key not found)

Return pointer to root of [potential] new subtree

1 if Return (empty subtree)
    Not found
    1 set success to false
    2 return null
2 end if
3 if (dltKey < root)
    1 set left-subtree to AVLDelete(left subtree, dltKey,
                                      success)
```

AVL Tree Delete (cont.)

```
2 if (tree shorter)
    1 set root to deleteRightBalance(root)
3 end if
4 elseif (dltKey > root)
    1 set right subtree to AVLDelete(root->right, dltKey,
                                         success)
    2 if (tree shorter)
        1 set root to deleteLeftBalance (root)
    3 end if
5 else
    Delete node found--test for leaf node
    1 save root
```

AVL Tree Delete (cont.)

```
2 if (no right subtree)
    1 set success to true
    2 return left subtree
3 elseif (no left subtree)
    Have right but no left subtree
    1 set success to true
    2 return right subtree
4 else
    Deleted node has two subtrees
    Find substitute--largest node on left subtree
    1 find largest node on left subtree
    2 save largest key
    3 copy data in largest to root
    4 set left subtree to AVLDelete(left subtree,
                                    largest key, success)
    5 if (tree shorter)
        1 set root to dltRightBal (root)
    6 end if
    5 end if
6 end if
7 return root
end AVLDelete
```

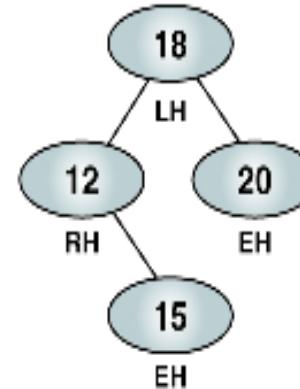
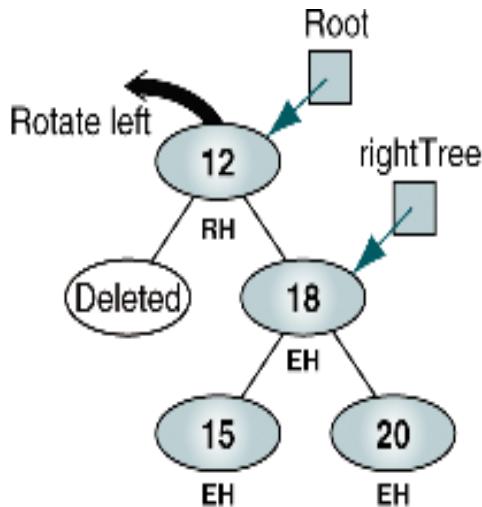
AVL Tree Delete Right Balance

```
Algorithm deleteRightBalance (root)
The [sub]tree is shorter after a deletion on the left branch.
If necessary, balance the tree by rotating.

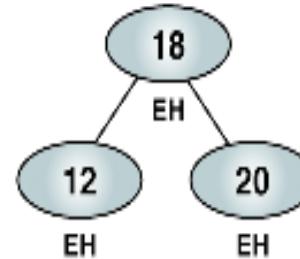
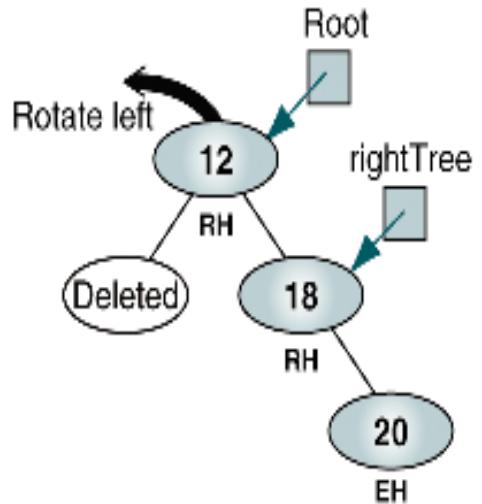
    Pre      tree is shorter
    Post     balance restored
    Return   new root

1 if (tree not balanced)
    No rotation required if tree left or even high
    1 set rightOfRight to right subtree
    2 if (rightOfRight left high)
        Double rotation required
        1 set leftOfRight to left subtree of rightOfRight
            Rotate right then left
        2 right subtree = rotateRight (rightOfRight)
        3 root           = rotateLeft (root)
    3 else
        Single rotation required
        1 set root to rotateLeft (root)
    4 end if
2 end if
3 return root
end deleteRightBalance
```

AVL Tree Delete Balance



(a) Right subtree is even balanced



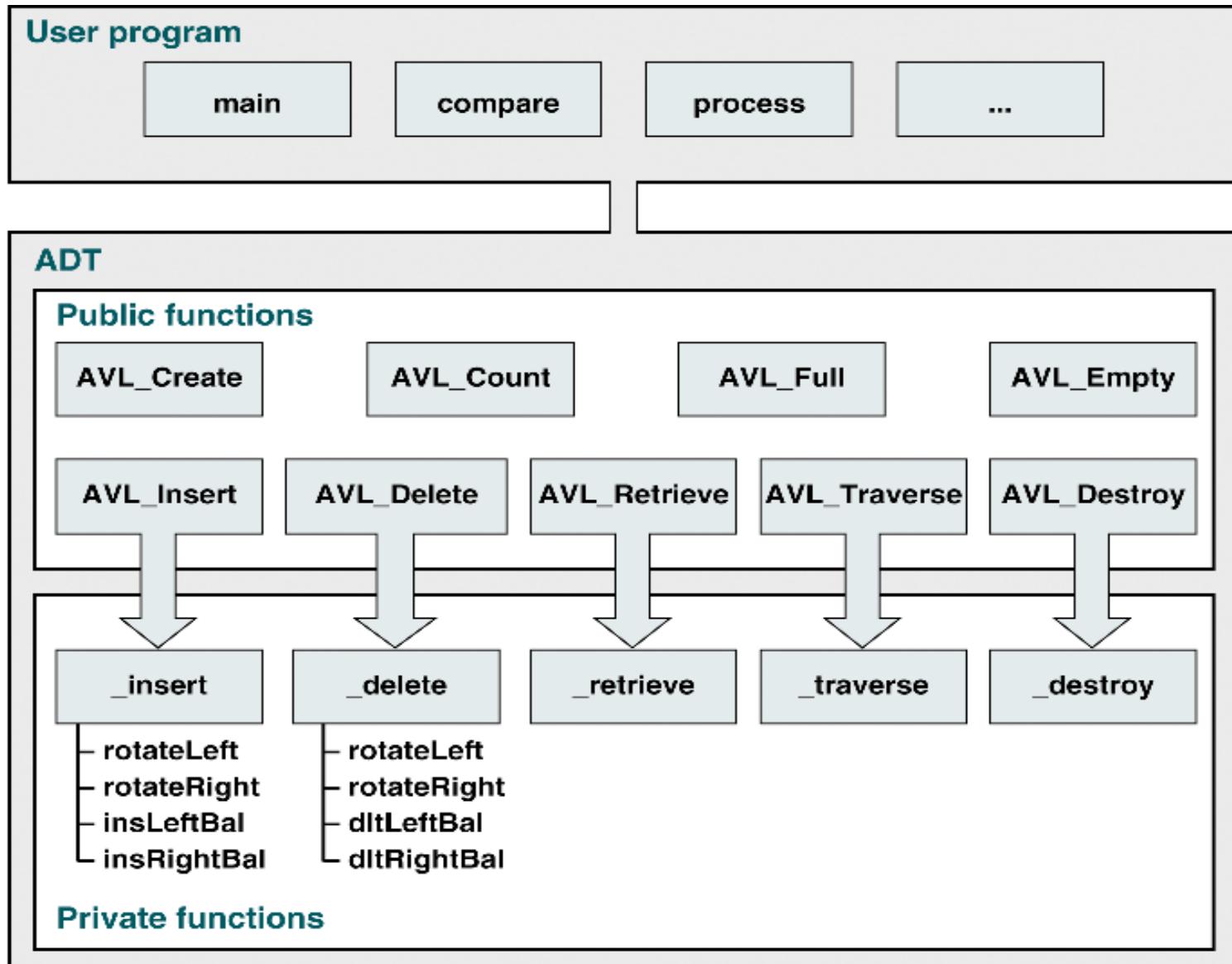
(b) Right subtree is not even balanced

8-3 AVL Tree Abstract Data Type

In this section we discuss and write the C code for the AVL ADT. We begin with a discussion of the data structure and then develop 17 functions for the ADT. Some functions are left for student development.

- Insert into AVL Tree
- AVL Tree Delete Algorithm

AVL Tree Design



AVL Tree Data Structure

AVL-TREE



NODE



```
typedef struct
{
    int    count;
    NODE* root;
    int    (*compare) (void* arg1, void* argu2);
} AVL_TREE;
```

```
typedef struct node
{
    struct node* left;
    void*        dataPtr;
    int         bal;
    struct node* right;
} NODE;
```

AVL Tree Declarations

```
1 #define LH +1                                // Left High
2 #define EH  0                                 // Even High
3 #define RH -1                               // Right High
4
5 // Structure Declarations
6 typedef struct node
7 {
8     void*          dataPtr;
9     struct node*  left;
10    int           bal;
11    struct node*  right;
12 } NODE;
13
14 typedef struct
15 {
16     int      count;
17     int      (*compare) (void* arg1, void* arg2);
18     NODE*   root;
19 } AVL_TREE;
```

AVL Tree Declarations (cont.)

```
20 // Prototype Declarations
21 AVL_TREE* AVL_Create
22             (int (*compare)(void* argu1, void* argu2));
23 AVL_TREE* AVL_Destroy (AVL_TREE* tree);
24
25     bool AVL_Insert    (AVL_TREE* tree,
26                         void* dataInPtr);
27     bool AVL_Delete    (AVL_TREE* tree,  void* dltKey);
28     void* AVL_Retrieve (AVL_TREE* tree,  void* keyPtr);
29     void  AVL_Traverse (AVL_TREE* tree,
30                         void (*process)(void* dataPtr));
31     int   AVL_Count    (AVL_TREE* tree);
32     bool  AVL_Empty    (AVL_TREE* tree);
33     bool  AVL_Full     (AVL_TREE* tree);
34
35
```

AVL Tree Declarations (cont.)

```
36 static NODE* _insert
37             (AVL_TREE* tree, NODE* root,
38              NODE* newPtr,    bool* taller);
39 static NODE* _delete
40             (AVL_TREE* tree,
41              NODE* root,      void* dltKey,
42              bool* shorter,   bool* success);
43 static void* _retrieve
44             (AVL_TREE* tree,
45              void* keyPtr,    NODE* root);
46 static void _traversal
47             (NODE* root,
48              void (*process)(void* dataPtr));
49 static void _destroy     (NODE* root);
50
51 static NODE* rotateLeft  (NODE* root);
52 static NODE* rotateRight (NODE* root);
53 static NODE* insLeftBal  (NODE* root, bool* taller);
54 static NODE* insRightBal (NODE* root, bool* taller);
55 static NODE* dltLeftBal  (NODE* root, bool* shorter);
56 static NODE* dltRightBal (NODE* root, bool* shorter);
```

Create AVL Tree Application Interface

```
1  /* ===== AVL_Create =====
2   Allocates dynamic memory for an AVL tree head
3   node and returns its address to caller.
4   Pre   compare is address of compare function
5       used when two nodes need to be compared
6   Post  head allocated or error returned
7   Return head node pointer; null if overflow
8 */
9  AVL_TREE* AVL_Create
10    (int (*compare) (void* arg1, void* arg2))
11 {
12 // Local Definitions
13     AVL_TREE* tree;
14
15 // Statements
16     tree = (AVL_TREE*) malloc (sizeof (AVL_TREE));
17     if (tree)
18     {
19         tree->root      = NULL;
20         tree->count     = 0;
21         tree->compare   = compare;
22     } // if
23
24     return tree;
25 } // AVL_Create
```

Insert AVL Tree Application Interface

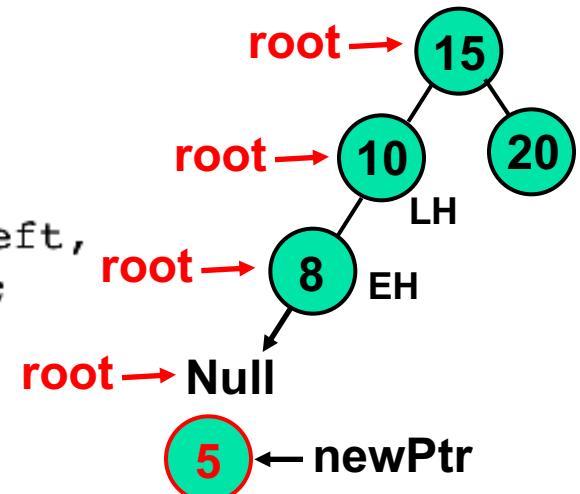
```
1  /* ===== AVL_Insert =====
2   This function inserts new data into the tree.
3   Pre    tree is pointer to AVL tree structure
4   Post   data inserted or memory overflow
5   Return Success (true) or Overflow (false)
6 */
7  bool AVL_Insert (AVL_TREE* tree, void* dataInPtr)
8  {
9  // Local Definitions
10  NODE* newPtr;
11  bool forTaller;
12
13 // Statements
14  newPtr = (NODE*)malloc(sizeof(NODE));
15  if (!newPtr)
16      return false;
17
18  newPtr->bal      = EH;
19  newPtr->right    = NULL;
20  newPtr->left     = NULL;
21  newPtr->dataPtr  = dataInPtr;
22
23  tree->root = _insert(tree,  tree->root,
24                      newPtr,      &forTaller);
25  (tree->count)++;
26  return true;
27 } // AVL_Insert
```

Internal Insert Function

```
1  /* ===== _insert =====
2   This function uses recursion to insert the new data
3   into a leaf node in the AVL tree.
4   Pre  Application has called AVL_Insert, which passes
5        root and data pointers.
6   Post Data have been inserted.
7   Return pointer to [potentially] new root.
8 */
9 NODE* _insert (AVL_TREE* tree,    NODE* root,
10                 NODE*      newPtr, bool* taller)
11 {
12 // Statements
13     if (!root)
14     {
15         // Insert at root
16         root      = newPtr;
17         *taller   = true;
18         return   root;
19     } // if NULL tree
```

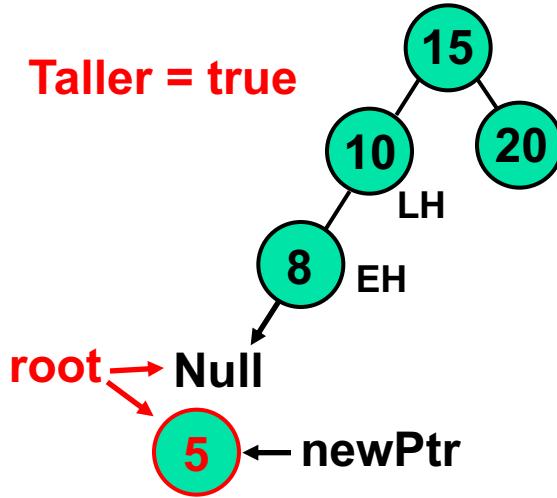
Internal Insert Function (cont.)

```
20
21    if (tree->compare(newPtr->dataPtr,
22                          root->dataPtr) < 0)
23    {
24        // newData < root -- go left
25        root->left = _insert(tree,    root->left,
26                               newPtr, taller);
27        if (*taller)
28            // Left subtree is taller
29            switch (root->bal)
30            {
31                case LH:   // Was left high--rotate
32                    root = insLeftBal (root, taller);
33                    break;
34
35                case EH:   // Was balanced--now LH
36                    root->bal = LH;
37                    break;
38
39                case RH:   // Was right high--now EH
40                    root->bal = EH;
```



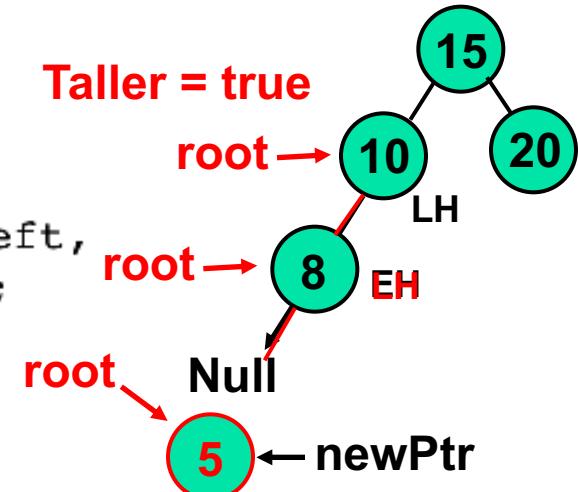
Internal Insert Function

```
1  /* ===== _insert =====
2   This function uses recursion to insert the new data
3   into a leaf node in the AVL tree.
4   Pre  Application has called AVL_Insert, which passes
5       root and data pointers.
6   Post  Data have been inserted.
7   Return pointer to [potentially] new root.
8 */
9  NODE* _insert (AVL_TREE* tree,    NODE* root,
10                 NODE*      newPtr, bool* taller)
11 {
12 // Statements
13 if (!root)
14 {
15     // Insert at root
16     root      = newPtr;
17     *taller   = true;
18     return   root;
19 } // if NULL tree
```



Internal Insert Function (cont.)

```
20
21     if (tree->compare(newPtr->dataPtr,
22                         root->dataPtr) < 0)
23     {
24         // newData < root -- go left
25         root->left = _insert(tree,    root->left,
26                               newPtr, taller);
27         if (*taller)
28             // Left subtree is taller
29             switch (root->bal)
30             {
31                 case LH:   // Was left high--rotate
32                     root = insLeftBal (root, taller);
33                     break;
34
35                 case EH:   // Was balanced--now LH
36                     root->bal = LH;
37                     break;
38
39                 case RH:   // Was right high--now EH
40                     root->bal = EH;
```

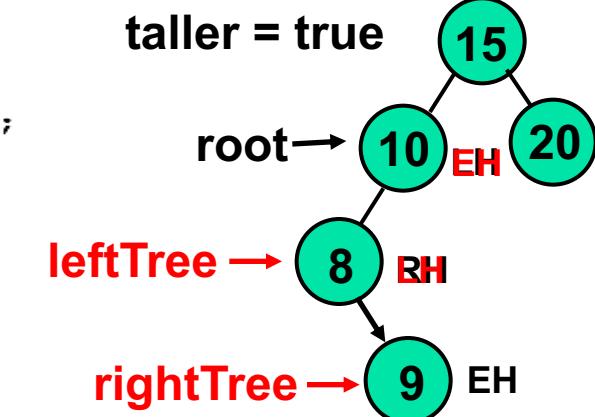
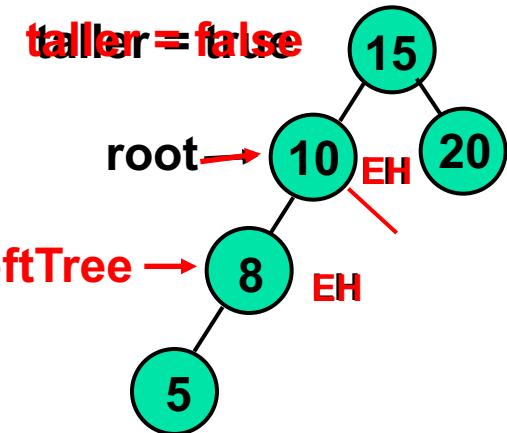


Internal Insert Function (cont.)

```
41             *taller    = false;
42             break;
43         } // switch
44         return root;
45     } // new < node
46 else
47     // new data >= root data
48 {
49     root->right = _insert (tree,    root->right,
50                           newPtr, taller);
51     if (*taller)
52         // Right subtree is taller
53         switch (root->bal)
54         {
55             case LH:   // Was left high--now EH
56                 root->bal = EH;
57                 *taller    = false;
58                 break;
59
60             case EH:   // Was balanced--now RH
61                 root->bal = RH;
62                 break;
63
64             case RH:   // Was right high--rotate
65                 root = insRightBal
66                               (root, taller);
67                 break;
68         } // switch
69         return root;
70     } // else new data >= root data
71     return root;
72 } // _insert
```

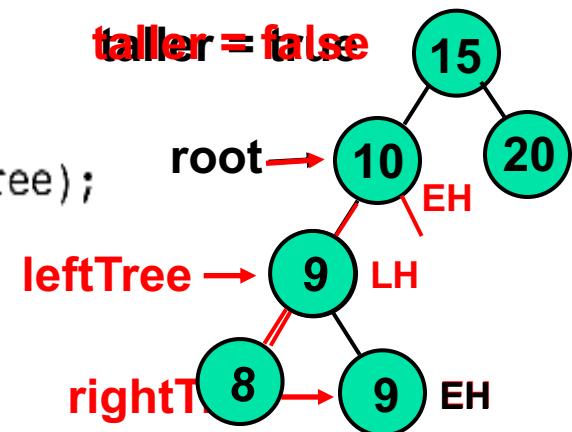
Internal Insert Left Balance Function

```
1  /* ===== insLeftBalance =====
2   Tree out-of-balance to the left. This function
3   rotates the tree to the right.
4     Pre The tree is left high
5     Post Balance restored; return potentially new root
6 */
7  NODE* insLeftBal (NODE* root, bool* taller)
8 {
9 // Local Definitions
10    NODE* rightTree;
11    NODE* leftTree;
12
13 // Statements
14    leftTree = root->left;
15    switch (leftTree->bal)
16    {
17      case LH: // Left High--Rotate Right
18        root->bal      = EH;
19        leftTree->bal = EH;
20
21        // Rotate Right
22        root      = rotateRight (root);
23        *taller  = false;
24        break;
25
26      case EH: // This is an error
27        printf ("\n\nError in insLeftBal\n");
28        exit (100);
29
30      case RH: // Right High-Requires double
31        // rotation: first left, then right
32        rightTree = leftTree->right;
33        switch (rightTree->bal)
34        {
35          case LH: root->bal      = RH;
36          leftTree->bal = EH;
37          break;
38
39          case EH: root->bal      = EH;
40          leftTree->bal = LH;
```



Internal Insert Left Balance Function (cont.)

```
38                     break;
39         case RH: root->bal      = EH;
40                         leftTree->bal = LH;
41                         break;
42     } // switch rightTree
43
44     rightTree->bal = EH;
45     // Rotate Left
46     root->left = rotateLeft (leftTree);
47
48     // Rotate Right
49     root      = rotateRight (root);
50     *taller   = false;
51 } // switch
52 return root;
53 } // leftBalance
```

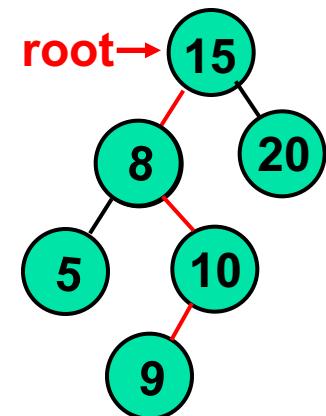


Internal Rotate Left & Right Function

```
1  /* ===== rotateLeft =====
2   Exchanges pointers to rotate the tree to the left.
3   Pre  root points to tree to be rotated
4   Post Node rotated and new root returned
5 */
6 NODE* rotateLeft (NODE* root)
7 {
8 // Local Definitions
9     NODE* tempPtr;
10
11 // Statements
12     tempPtr      = root->right;
13     root->right = tempPtr->left;
```

Internal Rotate Left & Right Function (cont.)

```
14     tempPtr->left = root;
15
16     return tempPtr;
17 } // rotateLeft
18
19 /* ====== rotateRight ======
20 Exchange pointers to rotate the tree to the right.
21 Pre root points to tree to be rotated
22 Post Node rotated and new root returned
23 */
24 NODE* rotateRight (NODE* root)
25 {
26 // Local Definitions
27     NODE* tempPtr;
28
29 // Statements
30     tempPtr          = root->left;
31     root->left      = tempPtr->right;
32     tempPtr->right   = root;
33
34     return tempPtr;
35 } // rotateRight
```



Delete AVL Tree Application Interface

```
1  /* ===== AVL_Delete =====
2   This function deletes a node from the tree and
3   rebalances it if necessary.
4   Pre   tree initialized--null tree is OK
5           dltKey is pointer to key to be deleted
6   Post  node deleted and its space recycled
7           -or- An error code is returned
8   Return Success (true) or Not found (false)
9 */
```

Delete AVL Tree Application Interface (cont.)

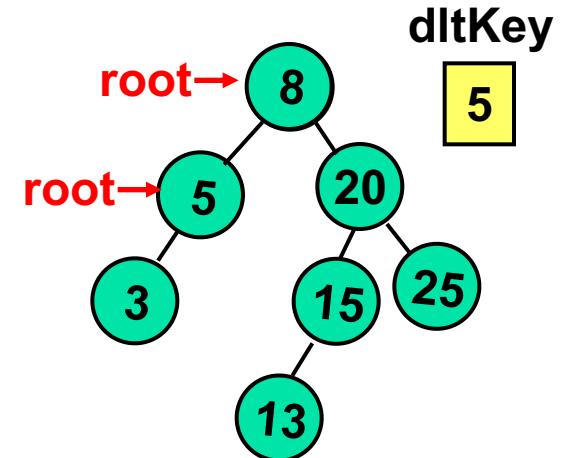
```
10  bool AVL_Delete (AVL_TREE* tree, void* dltKey)
11  {
12  // Local Definitions
13  bool shorter;
14  bool success;
15  NODE* newRoot;
16
17 // Statements
18 newRoot = _delete (tree,      tree->root, dltKey,
19                      &shorter, &success);
20 if (success)
21 {
22     tree->root = newRoot;
23     (tree->count)--;
24     return true;
25 } // if
26 else
27     return false;
28 } // AVL_Delete
```

Internal Delete Function

```
1  /* ===== _delete =====
2   Deletes node from the tree and rebalances
3   tree if necessary.
4   Pre    tree initialized--null tree is OK.
5           dltKey contains key of node to be deleted
6           shorter indicates tree is shorter
7   Post   node is deleted and its space recycled
8           -or- if key not found, tree is unchanged
9   Return true if deleted; false if not found
10      pointer to root
11  */
12
13 NODE* _delete (AVL_TREE* tree,  NODE* root,
14                 void*     dltKey, bool* shorter,
15                 bool*     success)
16 {
```

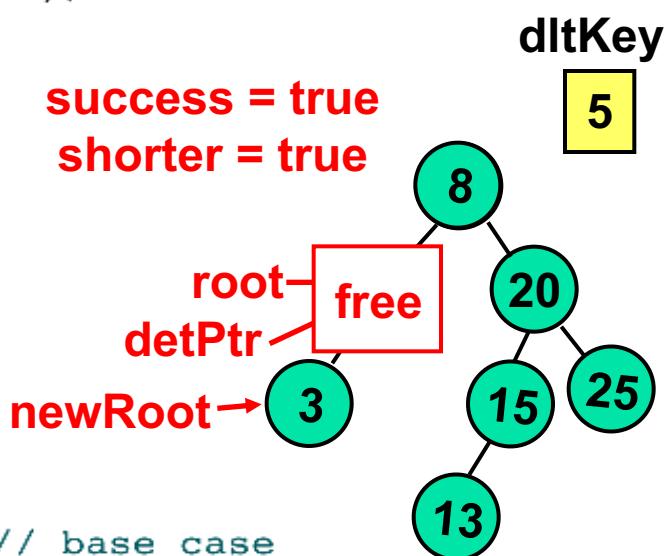
Internal Delete Function (cont.)

```
17 // Local Definitions
18     NODE* dltPtr;
19     NODE* exchPtr;
20     NODE* newRoot;
21
22 // Statements
23     if (!root)    // root = NULL
24     {
25         *shorter = false;
26         *success = false;
27         return NULL;
28     } // if
29
30     if (tree->compare(dltKey, root->dataPtr) < 0)
31     {
32         root->left = _delete (tree,
33                               root->left, dltKey,
34                               shorter,      success);
35         if (*shorter)
36             root = dltRightBal (root, shorter);
37     } // if less
```



Internal Delete Function (cont.)

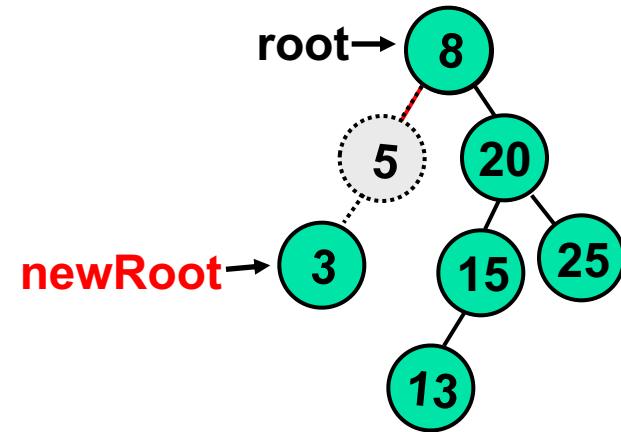
```
38     else if (tree->compare(dltKey, root->dataPtr) > 0)
39     {
40         root->right = _delete (tree,
41                               root->right, dltKey,
42                               shorter,      success);
43         if (*shorter)
44             root = dltLeftBal (root, shorter);
45     } // if greater
46 else
47     // Found equal node
48     {
49         dltPtr = root;
50         if (!root->right)
51             // Only left subtree
52             {
53                 newRoot = root->left;
54                 *success = true;
55                 *shorter = true;
56                 free (dltPtr);
57                 return newRoot;
58             } // if true
59     else
60         if (!root->left)
61             // Only right subtree
62             {
63                 newRoot = root->right;
```



Internal Delete Function (cont.)

```
17 // Local Definitions
18     NODE* dltPtr;
19     NODE* exchPtr;
20     NODE* newRoot;
21
22 // Statements
23     if (!root)
24     {
25         *shorter = false;
26         *success = false;
27         return NULL;
28     } // if
29
30     if (tree->compare(dltKey, root->dataPtr) < 0)
31     {
32         root->left = _delete (tree,
33                               root->left, dltKey,
34                               shorter,      success);
35         if (*shorter)
36             root = dltRightBal (root, shorter);
37     } // if less
```

success = true
shorter = true



Internal Delete Function (cont.)

```
64             *success = true;
65             *shorter = true;
66             free (dltPtr);
67             return newRoot;           // base case
68         } // if
69     else
70         // Delete Node has two subtrees
71     {
72         exchPtr = root->left;
73         while (exchPtr->right)
74             exchPtr = exchPtr->right;
75         root->dataPtr = exchPtr->dataPtr;
76         root->left = _delete (tree,
77                               root->left, exchPtr->dataPtr,
78                               shorter,    success);
79         if (*shorter)
80             root = dltRightBal (root, shorter);
81     } // else
82 } // equal node
83 return root;
84 } // _delete
```

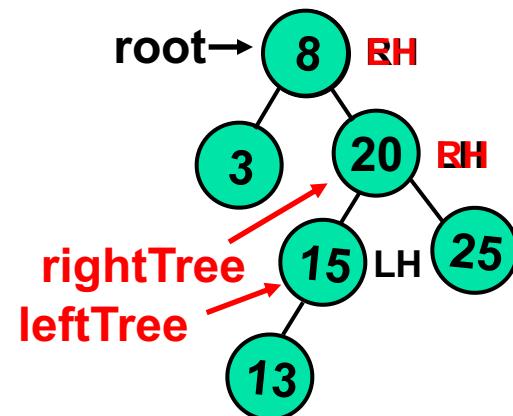
Internal Delete Right Balance Function

```
1  /* ===== dltRightBal =====
2   The tree is shorter after a delete on the left. This
3   function adjusts the balance factors and rotates
4   the tree to the left if necessary.
5     Pre      tree shorter
6     Post     Balance factors reset-balance restored
7     Returns potentially new root
8 */
9 NODE* dltRightBal (NODE* root, bool* shorter)
10 {
11 // Local Definitions
12     NODE* rightTree;
13     NODE* leftTree;
14
15 // Statements
16     switch (root->bal)
17     {
18         case LH:          // Deleted Left--Now balanced
19             root->bal = EH;
20             break;
```

Internal Delete Right Balance Function (cont.)

```
21  
22 case EH:          // Now Right high  
23     root->bal = RH;  
24     *shorter = false;  
25     break;  
26  
27 case RH:          // Right High - Rotate Left  
28     rightTree = root->right;  
29     if (rightTree->bal == LH)  
30         // Double rotation required  
31     {  
32         leftTree = rightTree->left;  
33  
34         switch (leftTree->bal)  
35         {  
36             case LH: rightTree->bal = RH;  
37                     root->bal      = EH;  
38             break;
```

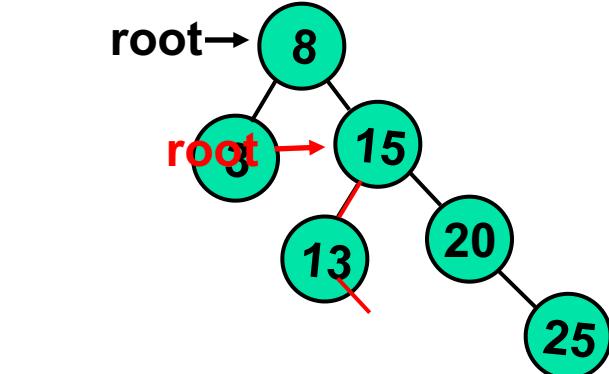
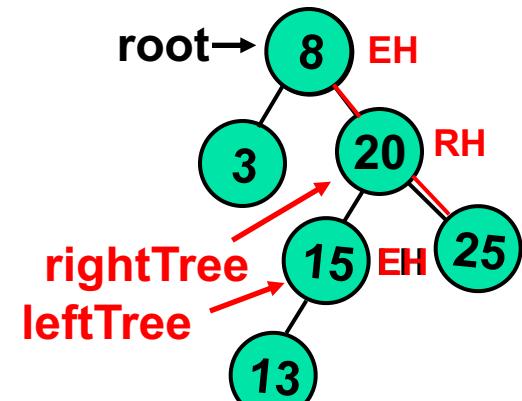
success = true
shorter = true



Internal Delete Right Balance Function (cont.)

```
39         case EH: root->bal      = EH;
40                 rightTree->bal = EH;
41                 break;
42         case RH: root->bal      = LH;
43                 rightTree->bal = EH;
44                 break;
45     } // switch
46
47     leftTree->bal = EH;
48
49     // Rotate Right then Left
50     root->right =
51             rotateRight (rightTree);
52     root = rotateLeft (root);
53 } // if rightTree->bal == LH
54 else
55 {
```

success = true
shorter = true



Internal Delete Right Balance Function (cont.)

```
56          // Single Rotation Only
57          switch (rightTree->bal)
58          {
59              case LH:
60              case RH: root->bal      = EH;
61                                rightTree->bal = EH;
62                                break;
63              case EH: root->bal      = RH;
64                                rightTree->bal = LH;
65                                *shorter      = false;
66                                break;
67          } // switch rightTree->bal
68          root = rotateLeft (root);
69      } // else
70  } // switch
71 return root;
72 } // dltRightBal
```

Retrieve AVL Tree Application interface

```
1  /* ====== AVL_Retrieve ======
2   Retrieve node searches tree for node containing
3   the requested key and returns pointer to its data.
4   Pre    Tree has been created (may be null)
5           data is pointer to data structure
6           containing key to be located
7   Post   Tree searched and data pointer returned
8   Return Address of matching node returned
9           If not found, NULL returned
10  */
11 void* AVL_Retrieve  (AVL_TREE* tree, void* keyPtr)
12 {
13 // Statements
14     if (tree->root)
15         return _retrieve (tree, keyPtr, tree->root);
16     else
17         return NULL;
18 } // AVL_Retrieve
```

Internal Retrieve Function

```
1  /* ===== _retrieve =====
2   Searches tree for node containing requested key
3   and returns its data to the calling function.
4   Pre    AVL_Retrieve passes tree, keyPtr, root
5           keyPtr is pointer to data structure
6           containing key to be located
7   Post   tree searched; data pointer returned
8   Return Address of matching node returned
9           if not found, NULL returned
10  */
11 void* _retrieve (AVL_TREE* tree,
12                  void*     keyPtr, NODE* root)
13 {
14 // Statements
15     if (root)
16     {
```

Internal Retrieve Function (cont.)

```
17     if (tree->compare(keyPtr, root->dataPtr) < 0)
18         return _retrieve(tree, keyPtr, root->left);
19     else if (tree->compare(keyPtr, root->dataPtr) > 0)
20         return _retrieve(tree, keyPtr, root->right);
21     else
22         // Found equal key
23         return root->dataPtr;
24     } // if root
25     else
26         // Data not in tree
27         return NULL;
28 } // _retrieve
```

Traverse AVL Tree Application Interface

```
1  /* ====== AVL_Traverse ======
2      Process tree using inorder traversal.
3          Pre   Tree has been created (may be null)
4                  process "visits" nodes during traversal
5          Post  Nodes processed in LNR (inorder) sequence
6 */
7  void AVL_Traverse (AVL_TREE* tree,
8                      void (*process) (void* dataPtr))
9  {
10 // Statements
11     _traversal (tree->root, process);
12     return;
13 } // end AVL_Traverse
```

Internal Traverse Function

```
1  /* ===== _traversal =====
2   Inorder tree traversal. To process a node, we use
3   the function passed when traversal was called.
4   Pre  Tree has been created (may be null)
5   Post All nodes processed
6 */
7 void _traversal (NODE* root,
8                  void (*process) (void* dataPtr))
9 {
10 // Statements
11 if  (root)
12 {
13     _traversal (root->left, process);
14     process    (root->dataPtr);
15     _traversal (root->right, process);
16 } // if
17 return;
18 } // _traversal
```

Empty AVL Tree Application Interface

```
1  /* ===== AVL_Empty =====
2   Returns true if tree is empty; false if any data.
3   Pre      Tree has been created. May be null
4   Returns  True if tree empty, false if any data
5 */
6  bool AVL_Empty (AVL_TREE* tree)
7  {
8  // Statements
9  return (tree->count == 0);
10 } // AVL_Empty
```

Full AVL Tree Application Interface

```
1  /* ====== AVL_Full ======
2   If there is no room for another node, returns true.
3   Pre      Tree has been created
4   Returns  True if no room for another insert,
5           false if room.
6 */
7  bool AVL_Full (AVL_TREE* tree)
8  {
9  // Local Definitions
10    NODE* newPtr;
11
12 // Statements
13  newPtr = (NODE*)malloc(sizeof (*(tree->root)));
14  if (newPtr)
15  {
16    free (newPtr);
17    return false;
18  } // if
19  else
20    return true;
21 } // AVL_Full
```

AVL Tree Count Application Interface

```
1  /* ===== AVL_Count =====
2   Returns number of nodes in tree.
3   Pre    Tree has been created
4   Returns tree count
5 */
6  int AVL_Count (AVL_TREE* tree)
7  {
8  // Statements
9  return (tree->count);
10 } // AVL_Count
```

Destroy AVL Tree Application Interface

```
1  /* ====== AVL_Destroy ======
2   Deletes all data in tree and recycles memory.
3   The nodes are deleted by calling a recursive
4   function to traverse the tree in inorder sequence.
5     Pre      tree is a pointer to a valid tree
6     Post     All data and head structure deleted
7     Return   null head pointer
8 */
9 AVL_TREE* AVL_Destroy (AVL_TREE* tree)
10 {
11 // Statements
12   if (tree)
13     _destroy (tree->root);
14
15 // All nodes deleted. Free structure
16 free (tree);
17 return NULL;
18 } // AVL_Destroy
```

Internal Destroy Function

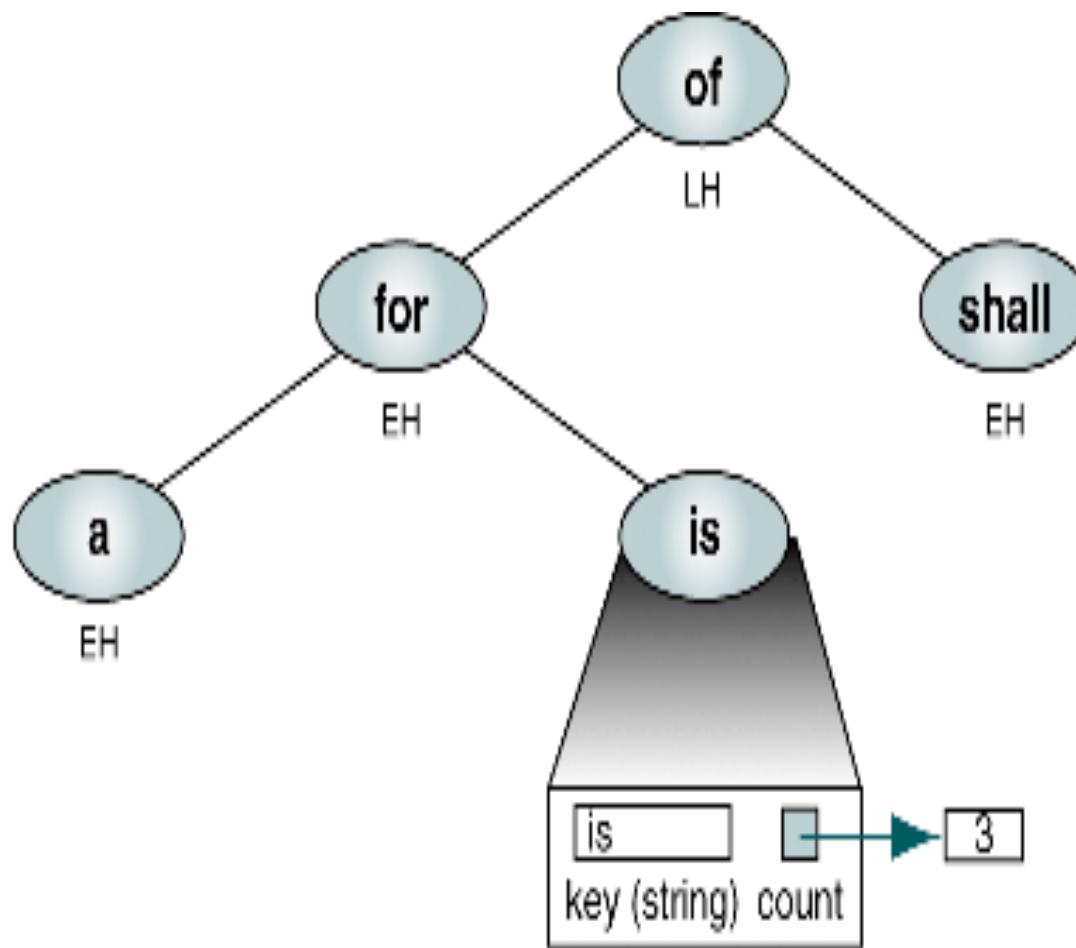
```
1  /* ===== _destroy =====
2   Deletes all data in tree and recycles memory.
3   The nodes are deleted by calling a recursive
4   function to traverse the tree in inorder sequence.
5   Pre      root is pointer to valid tree/subtree
6   Post     All data and head structure deleted
7   Return   null head pointer
8 */
9 void _destroy (NODE* root)
10 {
11 // Statements
12     if (root)
13     {
14         _destroy (root->left);
15         free (root->dataPtr);
16         _destroy (root->right);
17         free (root);
18     } // if
19     return;
20 } // _destroy
```

8-4 Application-Count Words

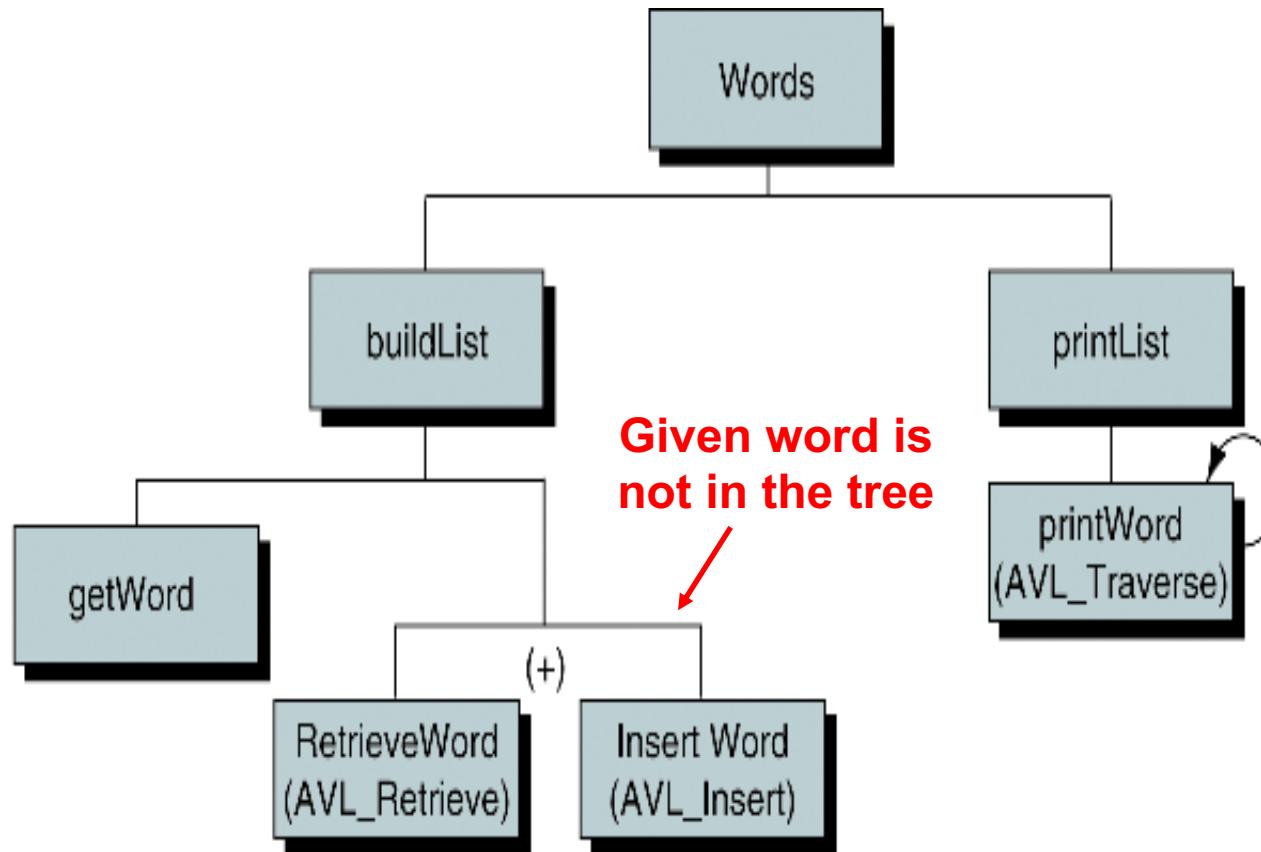
To demonstrate the use of an AVL tree, we write an application to count the words in a file. After discussing the application data structure, we write five functions, including main, to build and print the word list.

- Data Structure
- Program Design

Count Words Data Structure



Count Words Design



Count Words

```
1  /* This program counts the words in a file.  
2      Written by:  
3      Date:  
4  */  
5  #include <stdio.h>  
6  #include <string.h>  
7  #include <ctype.h>  
8  #include <stdlib.h>
```

Count Words (cont.)

```
9 #include <stdbool.h>
10 #include "P8AVLADT.h"
11
12 // Structures
13 typedef struct
14 {
15     char word[51];                                // One word
16     int count;
17 } DATA;
18
19 // Prototype Declarations
20 void buildList    (AVL_TREE*      wordList);
21 void insertWord   (AVL_TREE*      words);
22 void deleteWord   (AVL_TREE*      words);
23 void printList    (AVL_TREE*      wordList);
24 void printWord    (void* aWord);
25 bool getWord      (DATA* aWord,    FILE* fpWords);
26 int compareWords (void* arguPtr, void* listPtr);
```

Count Words (cont.)

```
27
28 int main (void)
29 {
30 // Local Definitions
31     AVL_TREE* wordList;
32
33 // Statements
34     printf("Start count words in document\n");
35     wordList = AVL_Create (compareWords);
36
37     buildList (wordList);
38     printList (wordList);
39
40     printf("End count words\n");
41     return 0;
42 } // main
```

Build List

```
1  /* ===== buildList =====
2   Reads file and creates AVL tree containing list
3   of all words used in the file with count of the
4   number of times each word is found in the file.
5   Pre   wordList has been created
6   Post  AVL tree (list) built or error returned
7 */
8 void buildList (AVL_TREE* wordList)
9 {
10 // Local Definitions
11 char fileName[25];
12 FILE* fpWords;
13
14 bool success;
```

Build List (cont.)

```
15     DATA* aWord;
16     DATA newWord;
17
18 // Statements
19 printf("Enter name of file to be processed: ");
20 scanf ("%24s", fileName);
21
22 fpWords = fopen (fileName, "r");
23 if (!fpWords)
24 {
25     printf("%-s could not be opened\a\n",fileName);
26     printf("Please verify name and try again.\n");
27     exit (100);
28 } // !fpWords
29
30 while (getWord (&newWord, fpWords))
31 {
32     aWord = AVL_Retrieve(wordList, &(newWord));
33     if (aWord)
34         (aWord->count)++;
35     else
36     {
37         aWord = (DATA*) malloc (sizeof (DATA));
38         if (!aWord)
39         {
40             printf("Error 120 in buildList\n");
41             exit (120);
42         } // if
43         // Add word to list
44         *aWord      = newWord;
45         aWord->count = 1;
46         success    = AVL_Insert (wordList, aWord);
47         if (!success)
48         {
```

Build List (cont.)

```
49         printf("Error 121 in buildList\n");
50         exit (121);
51     } // if overflow test
52 } // else
53 } // while
54
55 printf("End AVL Tree\n");
56 return;
57 } // buildList
```

Get Word

```
1  /* ===== getWord =====
2   Reads one word from file.
3   Pre  nothing
4   Post word read into reference parameter
5 */
6  bool getWord (DATA* aWord, FILE* fpWords)
7  {
8  // Local Definitions
9   char strIn[51];
10  int  ioResult;
11  int  lastChar;
12
13 // Statements
14 ioResult = fscanf(fpWords, "%50s", strIn);
15 if (ioResult != 1)
16   return false;
```

Get Word (cont.)

```
17 // Copy and remove punctuation at end of word.  
18 strcpy (aWord->word, strIn);  
19 lastChar = strlen(aWord->word) - 1;  
20 if (ispunct(aWord->word[lastChar]))  
21     aWord->word[lastChar] = '\0';  
22 return true;  
23 } // getWord
```

Compare Word Function

```
1  /* ===== compareWords =====
2   This function compares two integers identified
3   by pointers to integers.
4   Pre    arguPtr and listPtr are pointers to DATA
5   Return -1: arguPtr value <  listPtr value
6           -0: arguPtr value == listPtr value
7           +1: arguPtr value >  listPtr value
8 */
9  int compareWords (void* arguPtr, void* listPtr)
10 {
11 // Local Declarations
12     DATA arguValue;
13     DATA listValue;
14
15 // Statements
16     arguValue = *(DATA*)arguPtr;
17     listValue = *(DATA*)listPtr;
18
19     return (strcmp(arguValue.word, listValue.word));
20 } // compare
```

Print Word List

```
1  /* ===== printList =====
2   Prints the list with the count for each word.
3     Pre list has been built
4     Post list printed
5 */
6 void printList (AVL_TREE* wordList)
7 {
8 // Statements
9   printf("\nWords found in list\n");
10  AVL_Traverse (wordList, printWord);
11  printf("\nEnd of word list\n");
12  return;
13 } // printList
14
15 /* ===== printWord =====
16   Prints one word from the list with its count.
17     Pre ADT calls function to print data
18     Post data printed
19 */
20 void printWord (void* aWord)
21 {
22 // Statements
23   printf("%-25s %3d\n",
24         ((DATA*)aWord)->word, ((DATA*)aWord)->count);
25   return;
26 } // printWord
```

Results:

Start count words in document

Print Word List (cont.)

```
Enter name of file to be processed: gtsybrg.txt
```

```
End AVL Tree
```

```
Words found in list
```

| | |
|-----|---|
| But | 1 |
|-----|---|

| | |
|------|---|
| Four | 1 |
|------|---|

| | |
|-----|---|
| God | 1 |
|-----|---|

| | |
|----|---|
| It | 3 |
|----|---|

| | |
|-----|--|
| ... | |
|-----|--|

| | |
|-------|---|
| years | 1 |
|-------|---|

```
End of word list
```

```
End count words
```

Insertion into AVL Tree

