2 The Dictionary Problem: Search Trees

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The Dictionary Problem

The dictionary problem can be described as follows:

Given: a set of objects (data) where each element can be identified by a unique ***key*** (integer, string, ...).

Goal: a structure for storing the set of objects such that at least the following operations (methods) are supported:

- search (find, access)
- insert
- delete

The Dictionary Problem (2)

The following conditions can influence the choice of a solution to the dictionary problem:

- The place where the data are stored: main memory, hard drive, tape, WORM (write once read multiple)
- The frequency of the operations:
  – mostly insertion and deletion (dynamic)
  – mostly search (static)
  – approximately the same frequencies
  – not known
- Other operations to be implemented:
  – Enumerate the set in a certain order (e.g. ascending by key)
  – Set operations: union, intersection, difference quantity, ...
  – Split
  – construct
- Measure for estimating the solution: average case, worst case, amortized worst case
- Order of executing the operations:
  – sequential
  – concurrent

The Dictionary Problem (3)

Different approaches to the dictionary problem:

- Structuring the complete universe of all possible keys: hashing
- Structuring the set of the actually occurring keys: lists, trees, graphs, ...

Trees (1)

Trees are

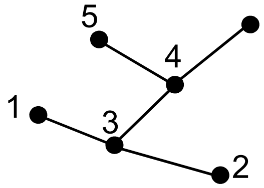
- generalized lists
  (each list element can have more than one successor)
- special graphs:
  – in general, a graph $G = (V,E)$ consists of a set V of vertices and a set $E \subseteq V \times V$ of edges.
  – the edges are either directed or undirected.
  – vertices and edges can be labelled (they contain further information).

  A tree is a connected acyclic graph, where:
  \# vertices = # edges + 1
- A general and central concept for the hierarchical structuring of information:
  – decision trees
  – code trees
  – syntax trees

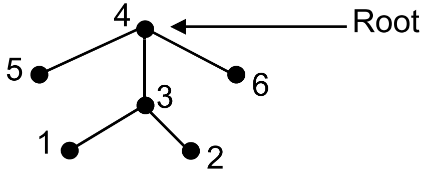
Trees (2)

Several kinds of trees can be distinguished:

- Undirected tree (with no designated root)



- Rooted tree (one node [= vertex] is designated as the root)



– From each node *k* there is exactly one path (a sequence of pairwise neighbouring edges) to the root

– the parent (or: direct predecessor) of a node *k* is the first neighbour on the path from *k* to the root

– the children (or: direct successors) are the other neighbours of *k*

– the rank (or: outdegree) of a node *k* is the number of children of *k*

Trees (3)

- Rooted tree:
  – root: the only node that has no parent
  – leaf nodes (leaves): nodes that have no children
  – internal nodes: all nodes that are not leaves
  – order of a tree *T*: maximum rank of a node in *T*
  – The notion *tree* is often used as a synonym for *rooted tree*.

- Ordered (rooted) tree: the children of each node are somehow ordered, i.e., there is the "leftmost child", the "second child from the left", ..., the "rightmost child".
  - In the graphical representation of a tree, this inevitably so.
  - In the formal definition of a tree, this is a-priori not the case. We have to explicitly state it.

- Binary tree: ordered tree of order 2; the children of a node (if there are 2) are referred to as left child and right child.

- Multiway tree: ordered tree of order > 2

Trees (4)

A more precise definition of the set M_d of the ordered rooted trees of order ($d \geq 1$):

Consider a set of nodes V.

- Each node in V is in M_d
- Let $t_1, \ldots, t_d \in M_d$ and w a node in V. Then w with the roots of $t_1, \ldots, t_d$ as its children (from left to right) is a tree $t \in M_d$. The t_i are subtrees of t.

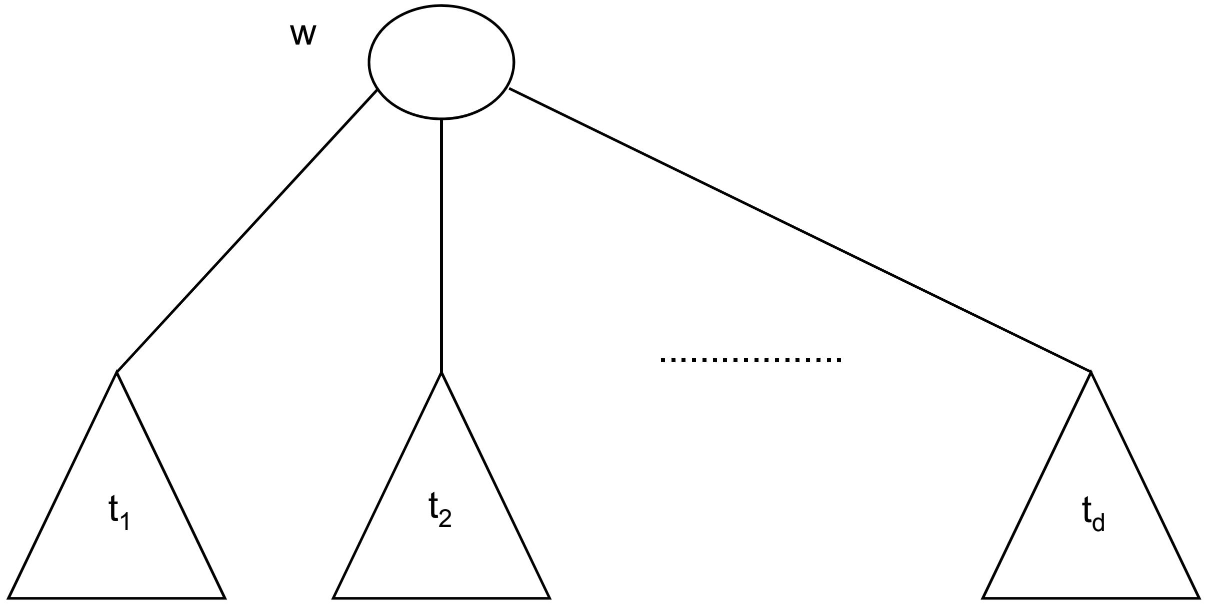
– According to this definition each node has rank d (or rank 0).

Nodes of binary trees either have 0 or 2 children.

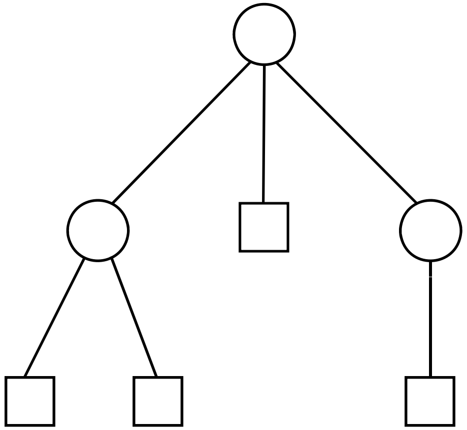
– Variation of the definition: allowing for rank $\leq d$.

For binary trees, nodes with exactly 1 child could then also be permitted.

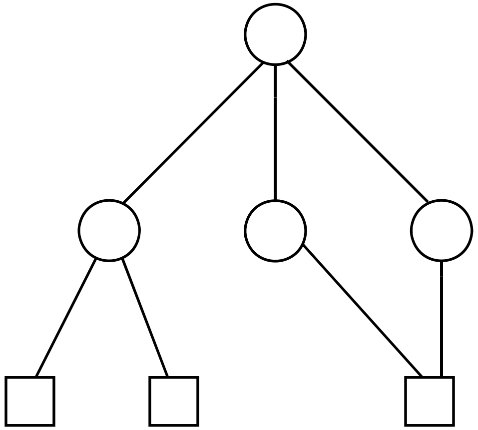
Illustration of the Definition



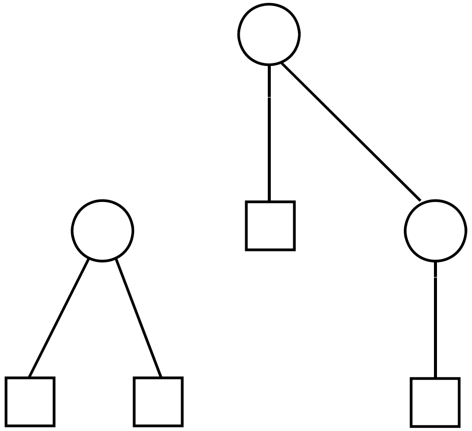
Examples



tree



not a tree



not a tree
(but two trees!)

Note that we chose to depict inner nodes as circles and leaves as boxes.

Structural Properties of Trees

- Depth of a node *k*: # edges from the tree root until *k* (distance of *k* to the root)
- Height *h*(*t*) of a tree *t*: maximum depth of a leaf in *t*.
  Alternative (recursive) definition:
  – $h(\text{leaf}) = 0$
  – $h(t) = 1 + \max\{t_i \mid \text{root of } t_i \text{ is a child of the root of } t\}$
  (t_i is a subtree of *t*)
- Level *i*: all nodes of depth *i*
- Complete tree: tree where each non-empty level has the maximum number of nodes.
  → all leaves have the same depth.

Labelled Vertices

- We mentioned that vertices (and edges) in a graph may be labelled, but in the above definitions on trees, we did not talk about labels yet – the set of nodes V was a “black box”.
- We now consider trees where either the inner nodes or the leaves or both are labelled.

Applications of Trees

Use of trees for the dictionary problem:

- Node: stores one data object
- Tree: stores a set of data
- Advantage (compared to hash tables): enumeration of the complete set of data (e.g. in ascending order) can be accomplished easily.

Standard Binary Search Trees (1)

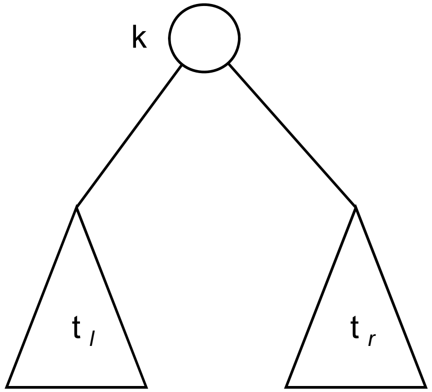
Goal: Storage, retrieval of data (more general: dictionary problem)

Two alternative ways of storage:

- Search trees: keys are stored in internal nodes
  leaf nodes are empty (usually = *null*), they represent intervals between the keys
- Leaf search trees: keys are stored in the leaves
  internal nodes contain information in order to direct the search for a key

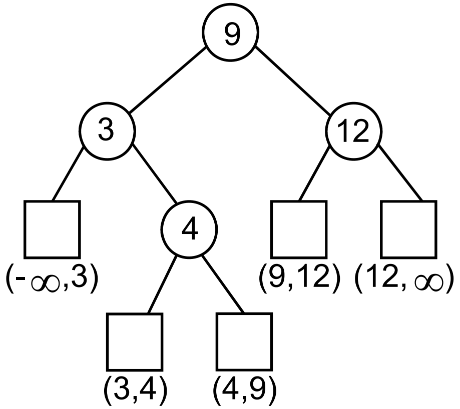
Search tree condition:

For each internal node *k*: all keys in the left subtree t_l of *k* are less (<) than the key in *k* and all keys in the right subtree t_r of *k* are greater (>) than the key in *k*



Standard Binary Search Trees (2)

Leaves in the search tree represent intervals between keys of the internal nodes



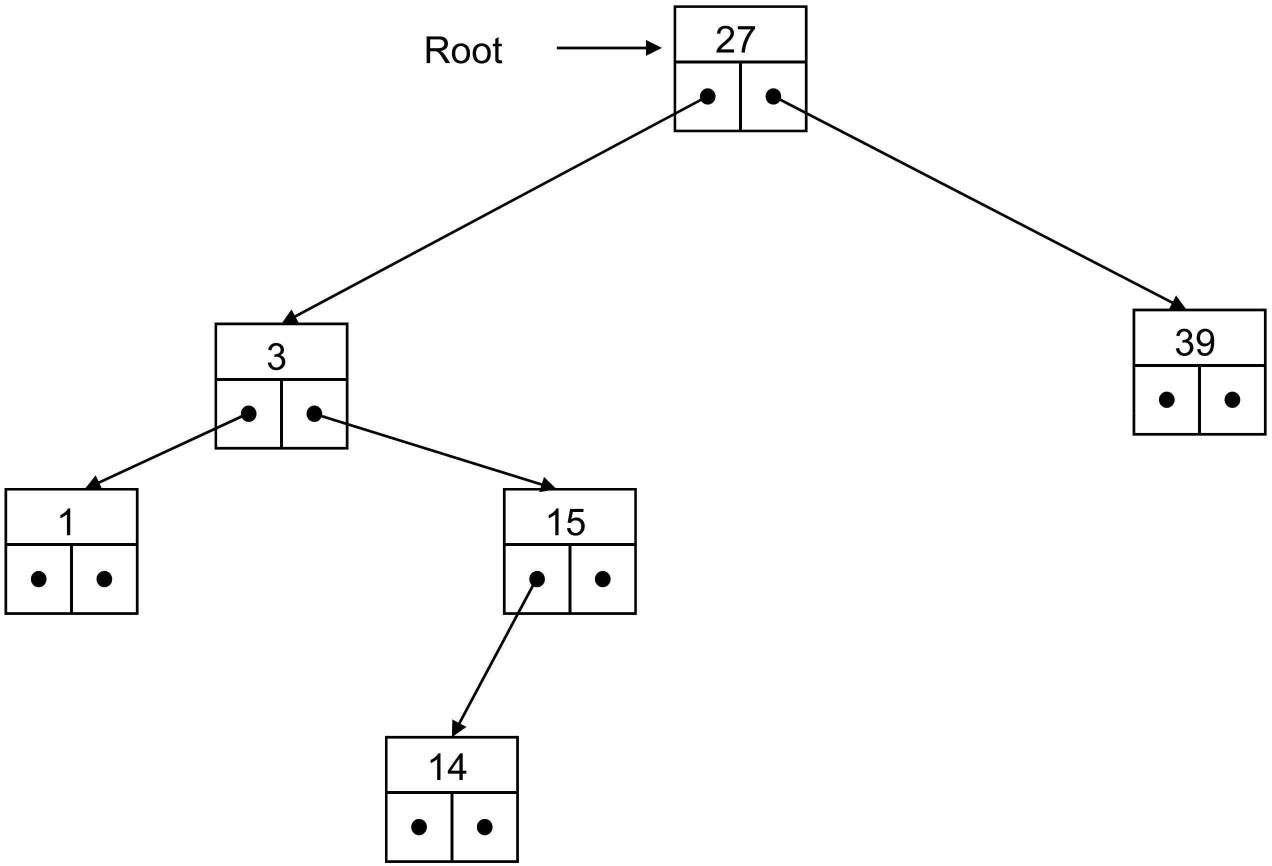
How can the search for key *s* be implemented? (leaf ≅ null)

```
k = root;
while (k != null) {
    if (s == k.key)     return true;
    if (s < k.key)      k = k.left;
    else             k = k.right
}
return false;
```

Example

Search for key *s* ends in the internal node *k* with *k.key* == *s*

or in the leaf whose interval contains *s*



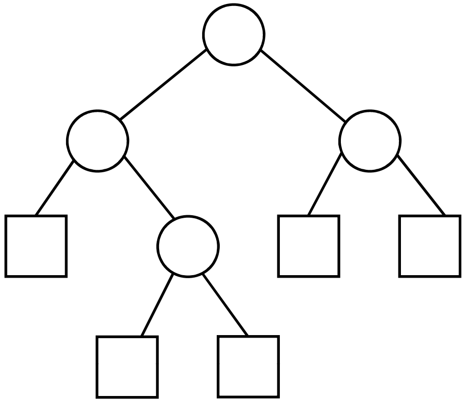
Standard Binary Search Trees (3)

Leaf search tree:

- Keys are stored in leaf nodes
- Clues (routers) are stored in internal nodes, such that $s_l \leq s_k < s_r$
  (s_l : key in left subtree, s_k : router in k, s_r : key in right subtree)
- Choice of s: maximum key in t_l .
- Alternative convention (less common): require $s_l < s_k \leq s_r$ and choose s as minimum key in t_r.

Example: leaf search tree

Leaf nodes store keys, internal nodes contain routers.



Example: leaf search tree

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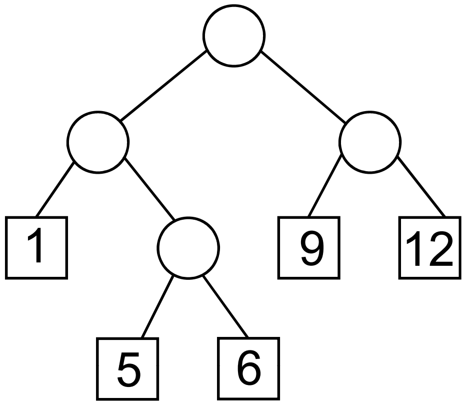
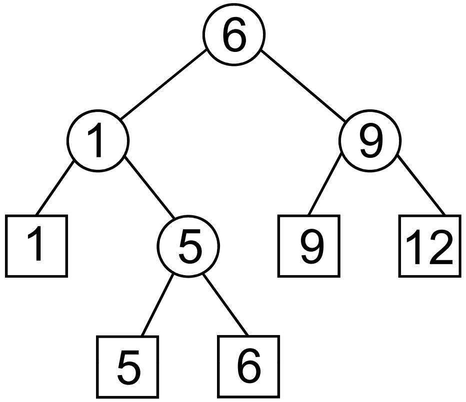


Example: leaf search tree

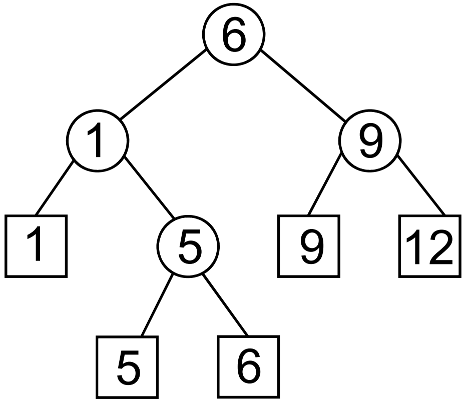
Leaf nodes store keys, internal nodes contain routers.



Standard Binary Search Trees (4)

How is the search for key *s* implemented in a leaf search tree?
(leaf = node with 2 *null* pointers)

```
k = root;
if (k == null) return false;
while (k.left != null) {                  // thus also k.right != null
    if (s <= k.key) k = k.left;
    else k = k.right;
}                                         // now in the leaf
return s==k.key;
```



From now on ...

- In the following we always talk about search trees (not leaf search trees).

Standard Binary Search Trees (5)

```
class SearchNode {
      int content;
      SearchNode left;
      SearchNode right;
      SearchNode (int c){ // Constructor for a node
          content = c;    // without successor
          left = right = null;
      }
  } //class SearchNode

  class SearchTree {
      SearchNode root;
      SearchTree () {     // Constructor for empty tree
          root = null;
      }
      // ...
  }
```

Standard Binary Search Trees (6)

```
/* Search for c in the tree */
   boolean search (int c) {
       return search (root, c);
   }
   boolean search (SearchNode n, int c){
       while (n != null) {
           if (c == n.content) return true;
           if (c < n.content) n = n.left;
           else n = n.right;
       }
       return false;
   }
```

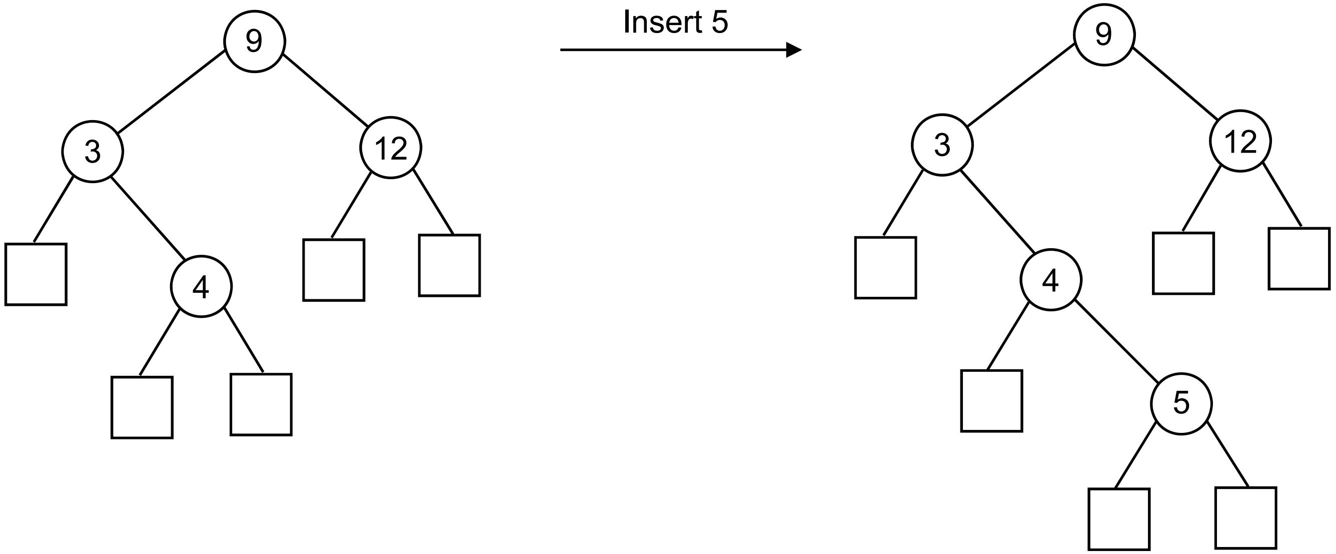
Standard Binary Search Trees (7)

Insertion of a node with key *s* in search tree *t*:

- Search for *s* ends in a node with *s*: don‘t insert (otherwise, there would be duplicated keys)
- Search ends in leaf *b*: make *b* an internal node with *s* as its key and two new leaves.

□ Tree remains a search tree!

Standard Binary Search Trees (8)



- Tree structure depends on the order of insertions into the initially empty tree
- Height can increase linearly, but it can also be in O(log n), more precisely $\lceil \log_2 (n+1) \rceil$.

Standard Binary Search Trees (9)

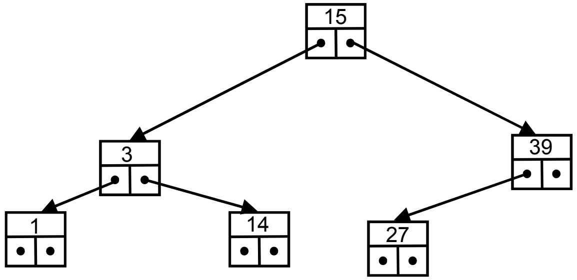
```
int height() {
        return height(root);
   }
   int height(SearchNode n){
        if (n == null) return 0;
        else return 1 + Math.max(height(n.left),
   height(n.right));
   }
   /* Insert c into tree; return true if successful
      and false if c was in tree already */
   boolean insert (int c) {       // insert c
        if (root == null){
            root = new SearchNode (c);
            return true;
        } else return insert (root, c);
   }
```

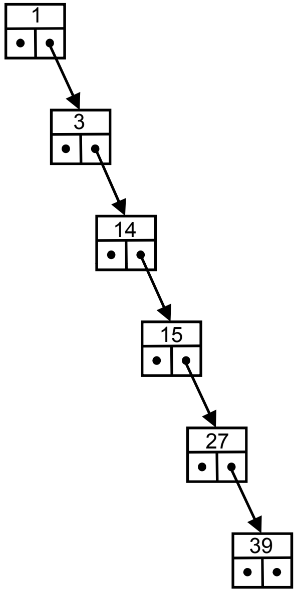
Standard Binary Search Trees (10)

```
boolean insert (SearchNode n, int c){
      while (true){
          if (c == n.content) return false;
          if (c < n.content){
              if (n.left == null) {
                  n.left = new SearchNode (c);
                  return true;
              } else n = n.left;
          } else {  // c > n.content
              if (n.right == null) {
                  n.right = new SearchNode (c);
                  return true;
              } else n = n.right;
          }
      }
  }
```

Special cases

- The structure of the resulting tree depends on the order in which the keys are inserted. The minimal height is $\lceil \log_2 (n+1) \rceil$ and the maximal height is n.
- Resulting search trees for the sequences 15, 39, 3, 27, 1, 14 and 1, 3, 14, 15, 27, 39:





Standard Binary Search Trees (11)

A standard tree is created by iterative insertions in an initially empty tree.

- Which trees are more frequent/typical: the balanced or the degenerate ones?
- How costly is an insertion?

We will address these questions in the next chapter.

Standard Binary Search Trees (11)

- Deletion of a node with key *s* from a tree (while retaining the search tree property)
- Search for *s*.
  If search fails: done.
  Otherwise search ends in node *k* with *k.key* == *s* and
- *k* has no child, one child or two children:
  (a) no child: done (set the parent's pointer to *null* instead of *k*)
  (b) only one child: let *k*'s parent *v* point to *k*'s child instead of *k*
  (c) two children: search for the smallest key in *k*'s right subtree, i.e. go right and then to the left as far as possible until you reach *p* (the symmetrical successor of *k*); copy *p.key* to *k*, delete *p* (which has at most one child, so follow step (a) or (b))

Symmetrical successor

Definition: A node *q* is called the symmetrical successor of a node *p* if *q* contains the smallest key greater than or equal to the key of *p*.

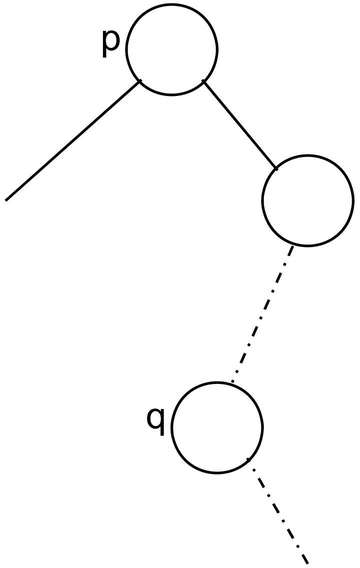
Observations:

- The symmetrical successor *q* of *p* is the leftmost node in the right subtree of *p*.
- The symmetrical successor has at most one child, which is the right child.

Finding the symmetrical successor

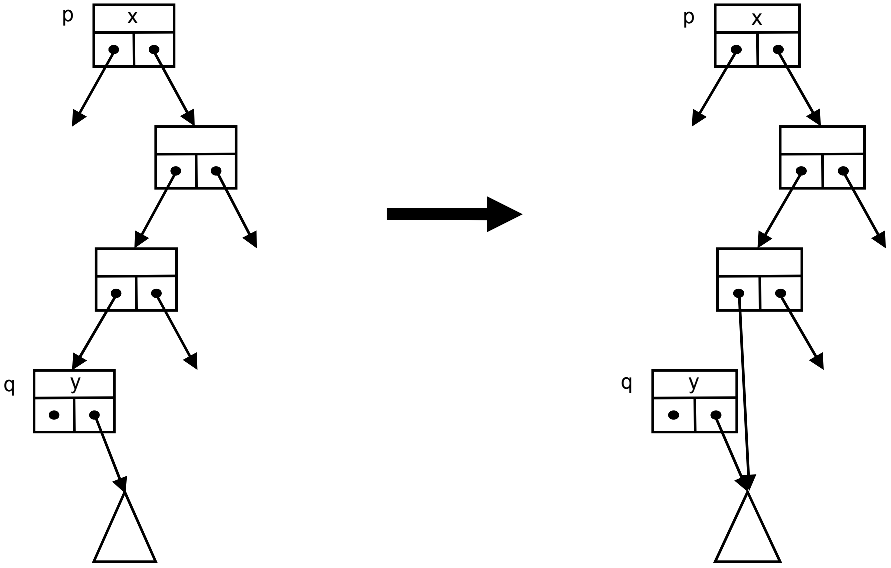
Observation: If *p* has a right child, the symmetrical successor always exists.

- First go to the right child of *p*.
- From there, always proceed to the left child until you find a node without a left child.



Idea of the *delete* operation

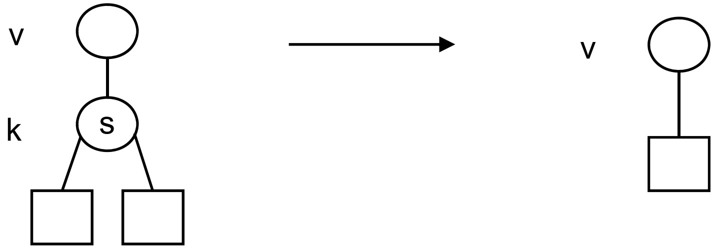
- Delete *p* by replacing its content with the content of its symmetrical successor *q.* Then delete *q*.
- Deletion of *q* is easy because *q* has at most one child.



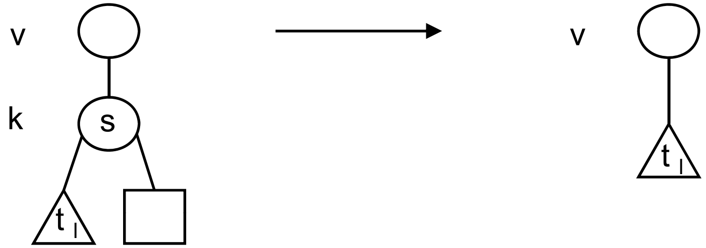
Illustration

k has no internal child or one internal child:

a)



b) (left)



b) (right)

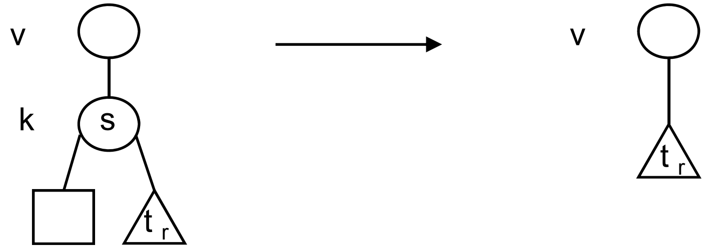
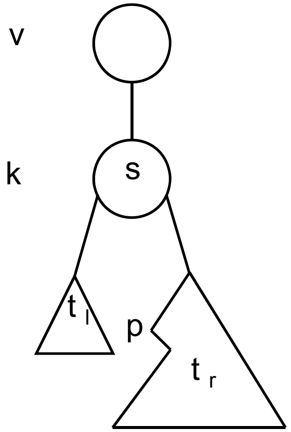


Illustration (2)

k has two internal children:

c)



Standard Binary Search Trees (12)

```
boolean delete(int c) {
       return delete(null, root, c);
   }
   // delete c from the tree rooted in n, whose parent is vn
   boolean delete(SearchNode vn, SearchNode n, int c) {
       if (n == null) return false;
       if (c < n.content) return delete(n, n.left, c);
       if (c > n.content) return delete(n, n.right, c);
       // now we have: c == n.content
       if (n.left == null) {
           point (vn, n, n.right);
           return true;
       }
       if (n.right == null) {
           point (vn, n, n.left);
           return true;
       }
       // ...
```

Standard Binary Search Trees (13)

```
// now n.left != null and n.right != null
      SearchNode q = pSymSucc(n);
      if (n == q) {   // right child of q is pSymSucc(n)
          n.content = q.right.content;
          q.right = q.right.right;
          return true;
      } else {        // left child of q is pSymSucc(n)
          n.content = q.left.content;
          q.left = q.left.right;
          return true;
      }
   } // boolean delete(SearchNode vn, SearchNode n, int c)
```

Standard Binary Search Trees (14)

```
// let vn point to m instead of n;
   // if vn == null, set root pointer to m
   void point(SearchNode vn, SearchNode n, SearchNode m) {
       if (vn == null) root = m;
       else if (vn.left == n) vn.left = m;
       else vn.right = m;
   }
   // returns the parent of the symmetrical successor
   SearchNode pSymSucc(SearchNode n) {
       if (n.right.left != null) {
           n = n.right;
           while (n.left.left != null) n = n.left;
       }
       return n;
   }
```