COMP2521 24T2
Binary Search Trees

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trees
binary search trees
binary search tree operations

Slides adapted from those by Kevin Luxa 2521 24T1

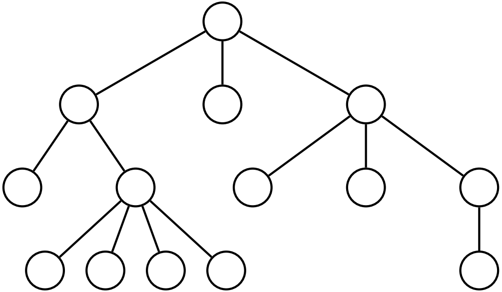
Trees

Trees

A tree is a hierarchical data structure
consisting of a set of connected nodes where:

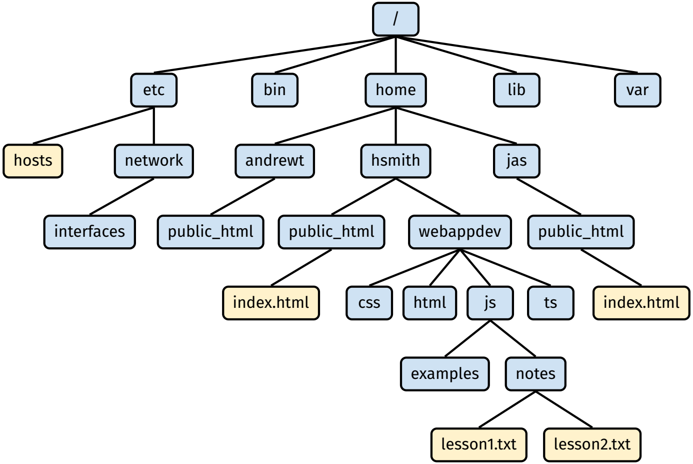
Each node may have multiple other nodes as children
(depending on the type of tree)

Each node is connected to one parent *except* the root node



Trees

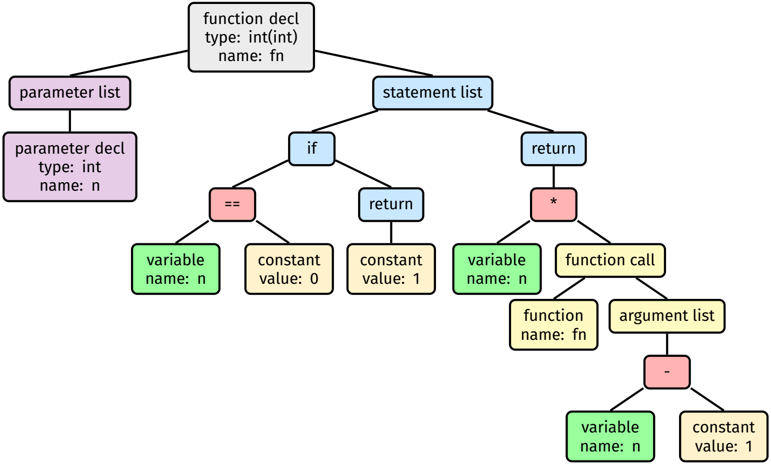
Example - File System Tree

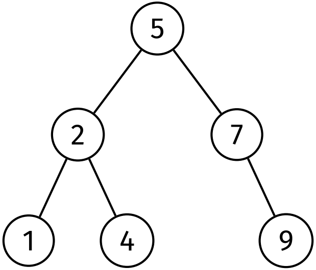


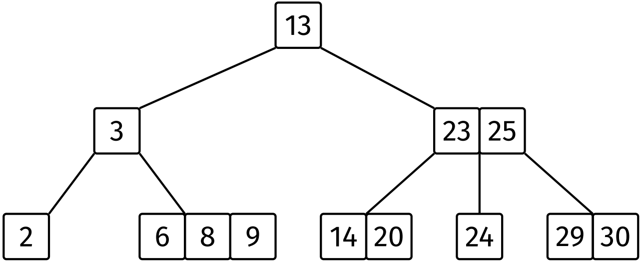
Source: https://www.openbookproject.net/tutorials/getdown/unix/lesson2.html

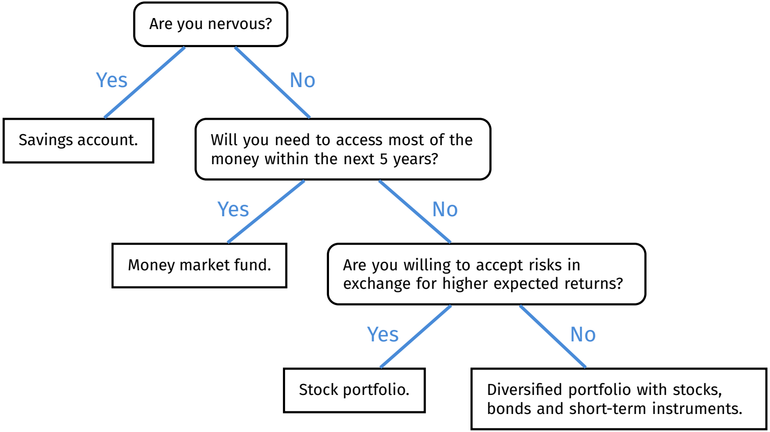
Trees

Example - Abstract Syntax Tree

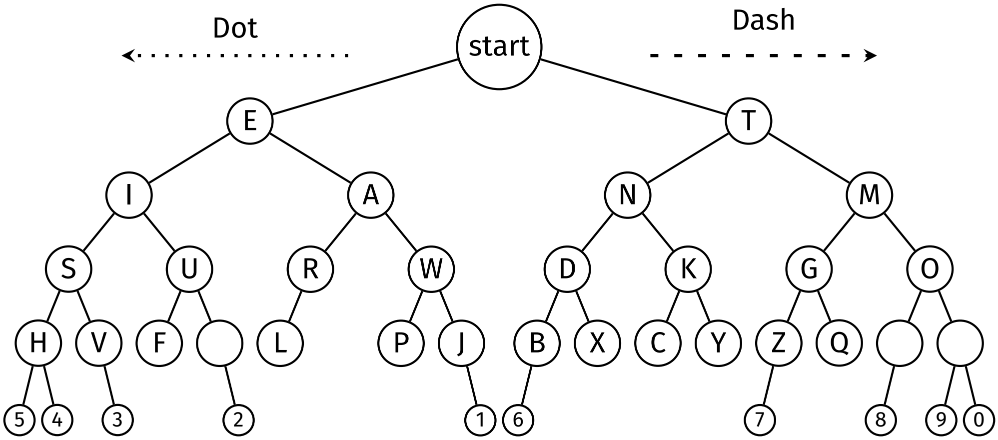



5
2
7
1
4
9


13
3
23
25
2
6
8
9
14
20
24
29
30



Source: “Data Structures and Algorithms in Java” (6th ed) by Goodrich et al.


Dot
start
Dash
E
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W
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P
J
B
X
C
Y
Z
Q
5
4
3
2
1
6
7
8
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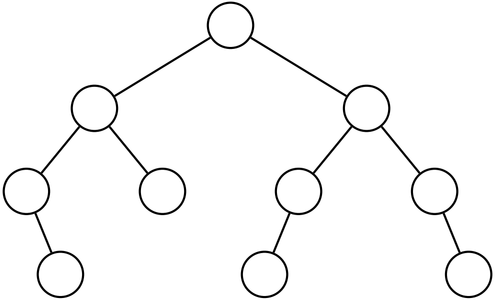
0

Binary Trees

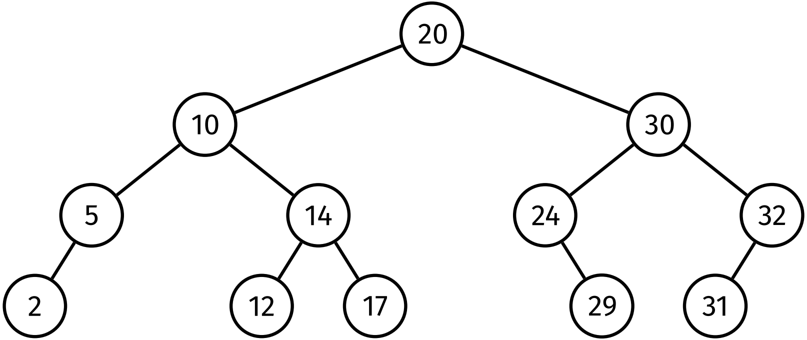
A binary tree is a tree where
each node can have up to two child nodes,
referred to as the left child and the right child.



Binary Search Trees

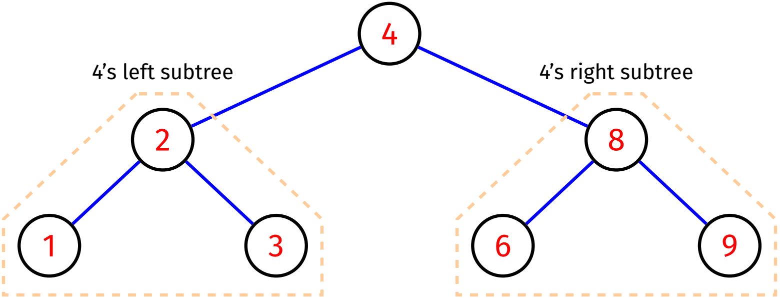
A binary search tree is an ordered binary tree, where *for each node*:

- All values in the left subtree are less than the value in the node
- All values in the right subtree are greater than the value in the node



A binary search tree is either:

- empty; or
- consists of a node with two subtrees
  - left and right subtrees are also BSTs (recursive)



Why use binary search trees?

Search is an extremely common operation in computing:

- selecting records in databases
- searching for pages on the web

Typically, there is a very large amount of data (very many items)

We need a more efficient way to search and maintain large amounts of data.

We've explored multiple approaches for searching:

- Ordered array
  - Searching/finding insertion point is $O(\log n)$ due to binary search
  - Inserting is $O(n)$ due to the need to shift items to preserve sortedness
- Ordered linked list
  - Searching/finding insertion point is $O(n)$ due to the nature of linked lists
  - Inserting *once we have found the insertion point* is $O(1)$ as there is no need to shift

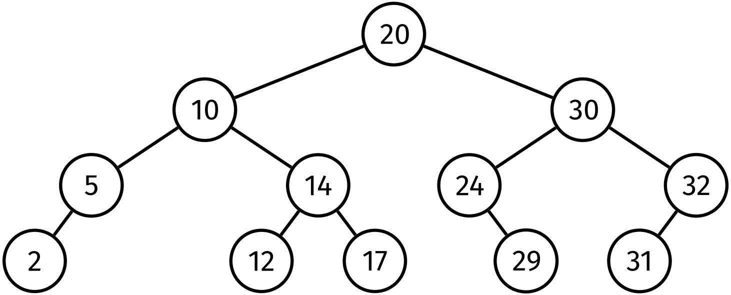
Binary Search Trees

Why?

Binary search trees are efficient to search *and* maintain:

- Searching in a binary search tree is similar to how binary search works
- A binary search tree is a linked data structure (like a linked list), so there is no need to shift elements when inserting/deleting

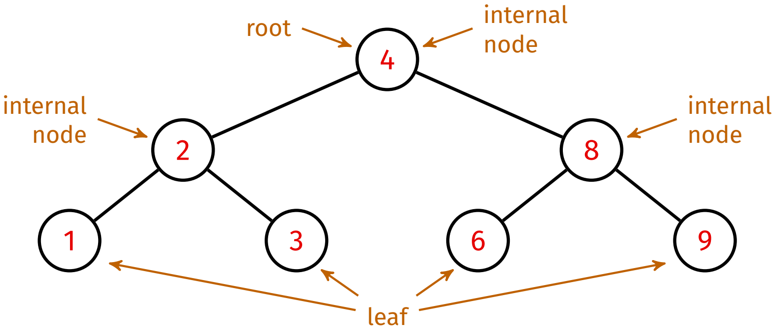
2	5	10	12	14	17	20	24	29	30	31	32



The root node is the node with no parent node.

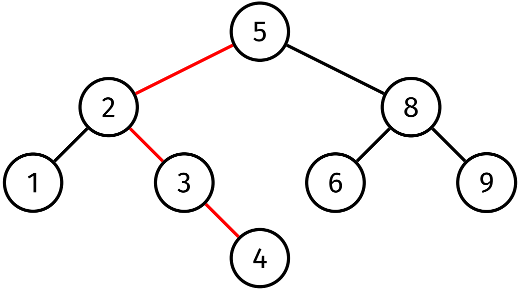
A leaf node is a node that has no child nodes.

An internal node is a node that has at least one child node.



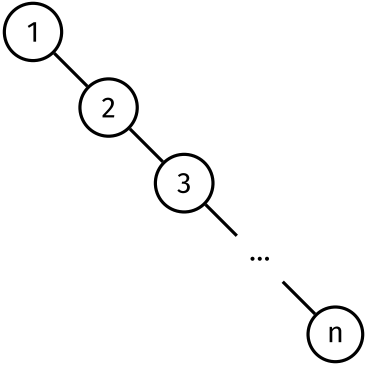
Height of a tree: Maximum path length from the root node to a leaf

- The height of an empty tree is considered to be -1
- The height of the following tree is 3



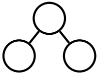
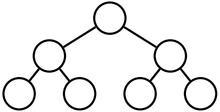
For a tree with n nodes:

The maximum possible height is $n - 1$



For a tree with n nodes:

The minimum possible height is $\lfloor \log_2 n \rfloor$

n	minimum height = $\lfloor \log_2 n \rfloor$	tree
1	0	
2-3	1	
4-7	2	
...	...	...

For a given number of nodes, a tree is said to be balanced if it has (close to) minimal height, and degenerate if it has (close to) maximal height.

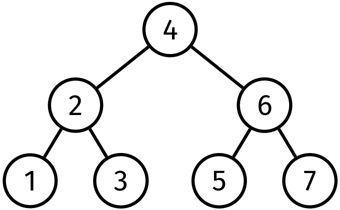
Binary trees are typically represented by node structures

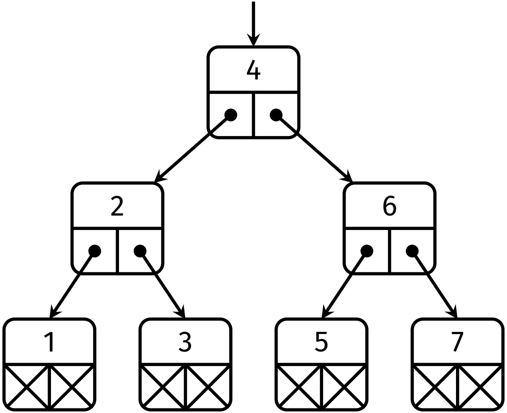
- Where each node contains a value and pointers to child nodes

```c
struct node {
    int item;
    struct node *left;
    struct node *right;
};
```

Binary Search Trees

Concrete Representation





Key operations on binary search trees:

- Insert
- Search
- Traversal
- Join
- Delete

The height h of a binary search tree determines the efficiency of many operations, so we will use both n and h in our analyses.

Insertion

bstInsert(t, v)

Given a BST t and a value v,
insert v into the BST
and return the root of the updated BST

BST Insertion

Insertion is straightforward:

- Start at the root
- Compare value to be inserted with value in the node
  - If value being inserted is less, descend to left child
  - If value being inserted is greater, descend to right child
- Repeat until...
  you have to go left/right but current node has no left/right child
  - Create new node and attach to current node

Recursive method:

- t is empty
  $\Rightarrow$ make a new node with v as the root of the new tree
- $v <$ t`->item`
  $\Rightarrow$ insert v into t's left subtree
- $v >$ t`->item`
  $\Rightarrow$ insert v into t's right subtree
- $v =$ t`->item`
  $\Rightarrow$ tree unchanged (assuming no duplicates)

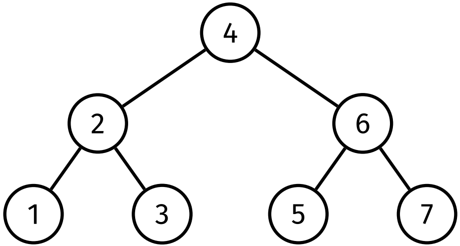
EXERCISE Try writing an iterative version.

BST Insertion

Example 1

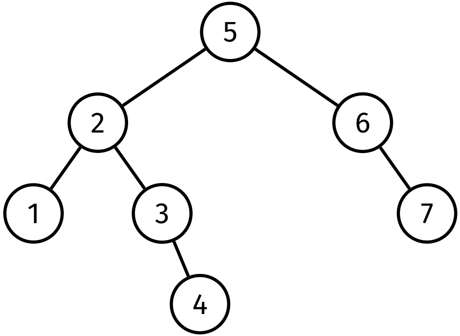
Insert the following values into an empty tree:

4 2 6 5 1 7 3



Insert the following values into an empty tree:

5 6 2 3 4 7 1

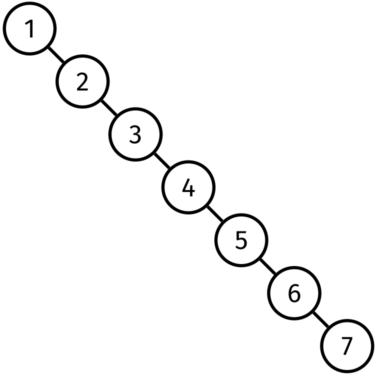


BST Insertion

Example 3

Insert the following values into an empty tree:

1 2 3 4 5 6 7



```
bstInsert(t, v):
    Input:  tree t, value v
    Output: t with v inserted

    if t is empty:
        return new node containing v
    else if v < t->item:
        t->left = bstInsert(t->left, v)
    else if v > t->item:
        t->right = bstInsert(t->right, v)

    return t
```

Analysis:

- At most one node is examined on each level
- Number of operations performed per node is constant
- Therefore, the worst-case time complexity of insertion is $O(h)$ where h is the height of the BST

Search

`bstSearch(`t`, `v`)`

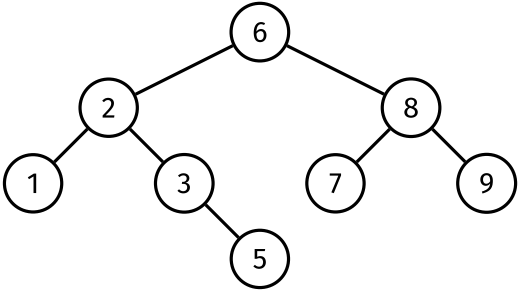
Given a BST t and a value v, return true if v is in the BST and false otherwise

Recursive method:

- t is empty:
  $\Rightarrow$ return false
- $v <$ t`->item`
  $\Rightarrow$ search for v in t's left subtree
- $v >$ t`->item`
  $\Rightarrow$ search for v in t's right subtree
- $v =$ t`->item`
  $\Rightarrow$ return true

EXERCISE Try writing an iterative version.

Search for 4 and 7 in the following BST:



```
bstSearch(t, v):
    Input:  tree t, value v
    Output: true if v is in t
            false otherwise

    if t is empty:
        return false
    else if v < t->item:
        return bstSearch(t->left, v)
    else if v > t->item:
        return bstSearch(t->right, v)
    else:
        return true
```

Analysis:

- At most one node is examined on each level
- Number of operations performed per node is constant
- Therefore, the worst-case time complexity of search is $O(h)$ where h is the height of the BST

Traversal

Given a BST,
visit every node of the tree

Tree Traversal

There are 4 common ways to traverse a binary tree:

1. Pre-order (NLR):
   visit root, then traverse left subtree, then traverse right subtree
2. In-order (LNR):
   traverse left subtree, then visit root, then traverse right subtree
3. Post-order (LRN):
   traverse left subtree, then traverse right subtree, then visit root
4. Level-order:
   visit root, then its children, then their children, and so on

Pseudocode:

```
preorder(t):
    Input: tree t

    if t is empty:
        return

    visit(t)
    preorder(t->left)
    preorder(t->right)
```

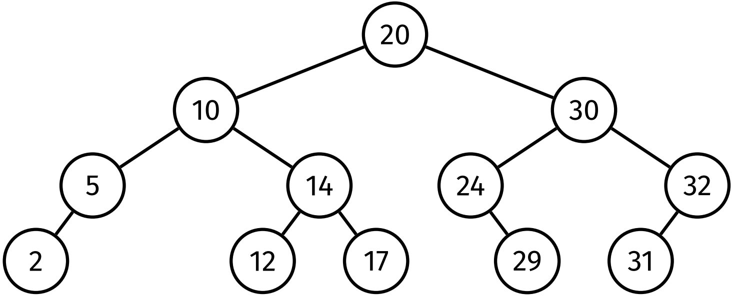
```
inorder(t):
    Input: tree t

    if t is empty:
        return

    inorder(t->left)
    visit(t)
    inorder(t->right)
```

```
postorder(t):
    Input: tree t

    if t is empty:
        return

    postorder(t->left)
    postorder(t->right)
    visit(t)
```

Note:
Level-order traversal is difficult to implement recursively.
It is typically implemented using a queue.

Tree Traversal

Example: Binary Search Tree

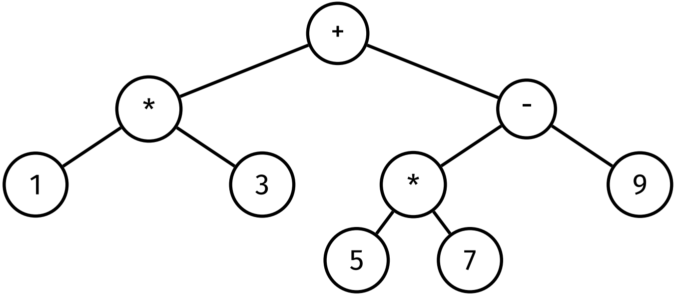


Pre-order	20 10 5 2 14 12 17 30 24 29 32 31
In-order	2 5 10 12 14 17 20 24 29 30 31 32
Post-order	2 5 12 17 14 10 29 24 31 32 30 20
Level-order	20 10 30 5 14 24 32 2 12 17 29 31

Tree Traversal

Example: Expression Tree

Expression tree for 1 * 3 + (5 * 7 - 9)



Pre-order	+ * 1 3 - * 5 7 9
In-order	1 * 3 + 5 * 7 - 9
Post-order	1 3 * 5 7 * 9 - +

Pre-order traversal:

- Useful for reconstructing a tree

In-order traversal:

- Useful for traversing a BST in ascending order

Post-order traversal:

- Useful for evaluating an expression tree
- Useful for freeing a tree

Level-order traversal:

- Useful for printing a tree

Analysis:

- Each node is visited once
- Hence, time complexity of tree traversal is $O(n)$, where n is the number of nodes

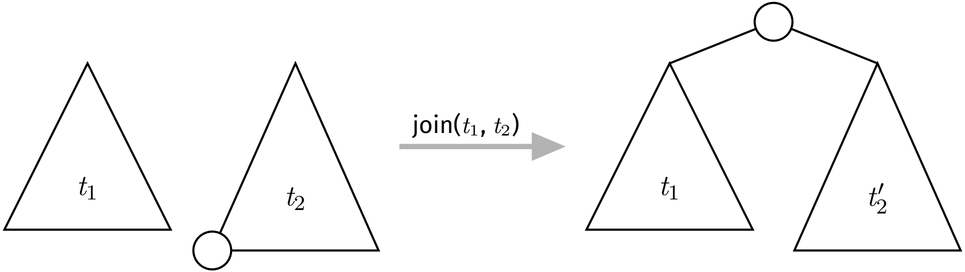
Join

`bstJoin(`t_1`, `t_2`)`

Given two BSTs t_1 and t_2
where $\max(t_1) < \min(t_2)$
return a BST containing all items from t_1 and t_2

Method:

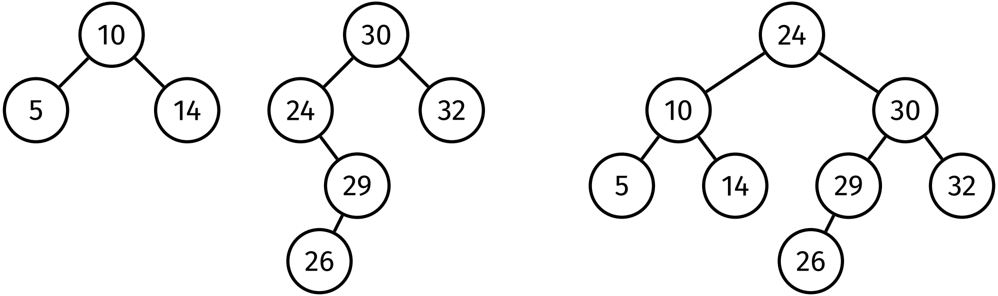
1. Find the minimum node min in t_2
2. Replace min by its right subtree (if it exists)
3. Elevate min to be the new root of t_1 and t_2



BST Join

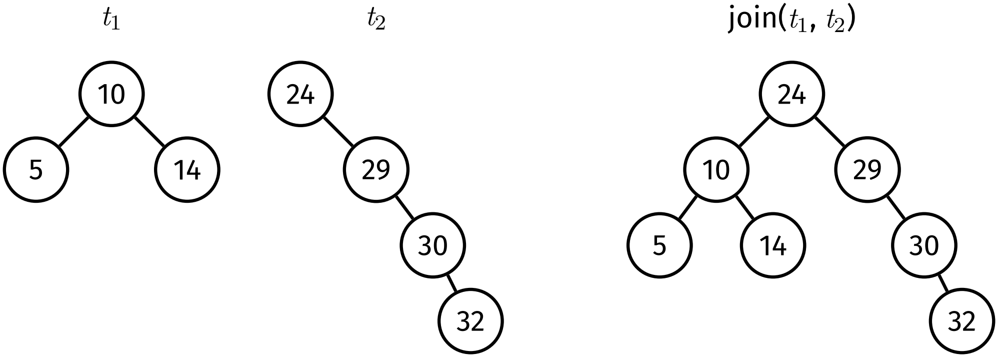
Example 1

t_1 t_2 join(t_1, t_2)



BST Join

Example 2



BST Join

Pseudocode


```
bstJoin(t1, t2):
    Input:  trees t1, t2
    Output: t1 and t2 joined together

    if t1 is empty:
        return t2
    else if t2 is empty:
        return t1
    else:
        curr = t2
        parent = NULL
        while curr->left ≠ NULL:
            parent = curr
            curr = curr->left

        if parent ≠ NULL:
            parent->left = curr->right
            curr->right = t2

        curr->left = t1
        return curr
```

Analysis:

- The join algorithm simply finds the minimum node in t_2
- Thus, at most one node is visited per level of t_2
- Therefore, the worst-case time complexity of join is $O(h_2)$ where h_2 is the height of t_2

Deletion

`bstDelete(`t`, `v`)`

Given a BST t and a value v
delete v from the BST
and return the root of the updated BST

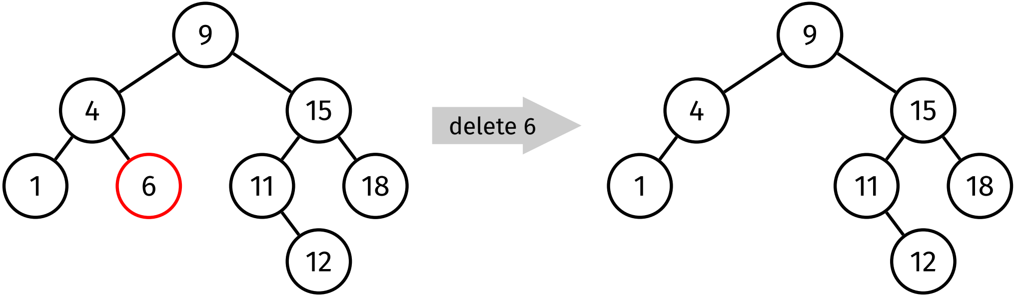
Recursive method:

- t is empty:
  $\Rightarrow$ result is empty
- $v <$ t`->item`
  $\Rightarrow$ delete v from t's left subtree
- $v >$ t`->item`
  $\Rightarrow$ delete v from t's right subtree
- $v =$ t`->item`
  $\Rightarrow$ three sub-cases:
  - t is a leaf
    $\Rightarrow$ result is empty tree
  - t has one subtree
    $\Rightarrow$ replace with subtree
  - t has two subtrees
    $\Rightarrow$ join the two subtrees

BST Deletion

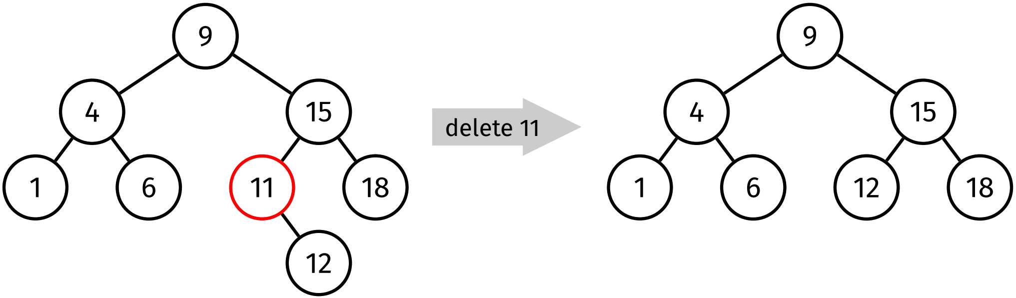
Examples

If the node being deleted is a leaf, then the result is an empty tree

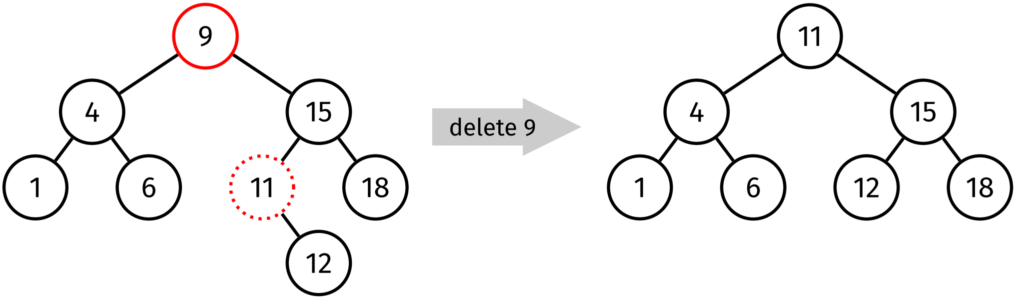


BST Deletion
Examples

Node to be deleted has one subtree



Node to be deleted has two subtrees



```
bstDelete(t, v):
    Input:  tree t, value v
    Output: t with v deleted

    if t is empty:
        return empty tree
    else if v < t->item:
        t->left = bstDelete(t->left, v)
    else if v > t->item:
        t->right = bstDelete(t->right, v)
    else:
        if t->left is empty:
            new = t->right
        else if t->right is empty:
            new = t->left
        else:
            new = bstJoin(t->left, t->right)

        free(t)
        t = new

    return t
```

Analysis:

- The deletion algorithm traverses down just one branch
  - First, the item being deleted is found
  - If the item exists and has two subtrees, its successor is found
- Thus, at most one node is visited per level
- Therefore, the worst-case time complexity of deletion is $O(h)$ where h is the height of the BST

BST Exercises

- `bstFree`
  free a tree
- `bstSize`
  return the size of a tree
- `bstHeight`
  return the height of a tree
- `bstPrune`
  given values lo and hi, remove all values outside the range $[lo, hi]$

Feedback

https://forms.office.com/r/riGKCze1cQ