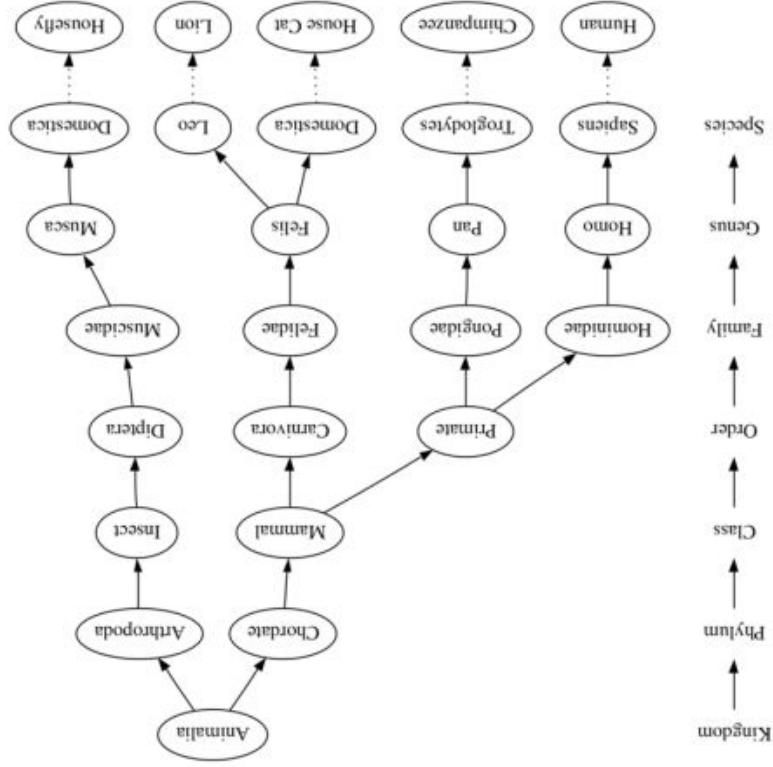


Scientific Programming: Part B

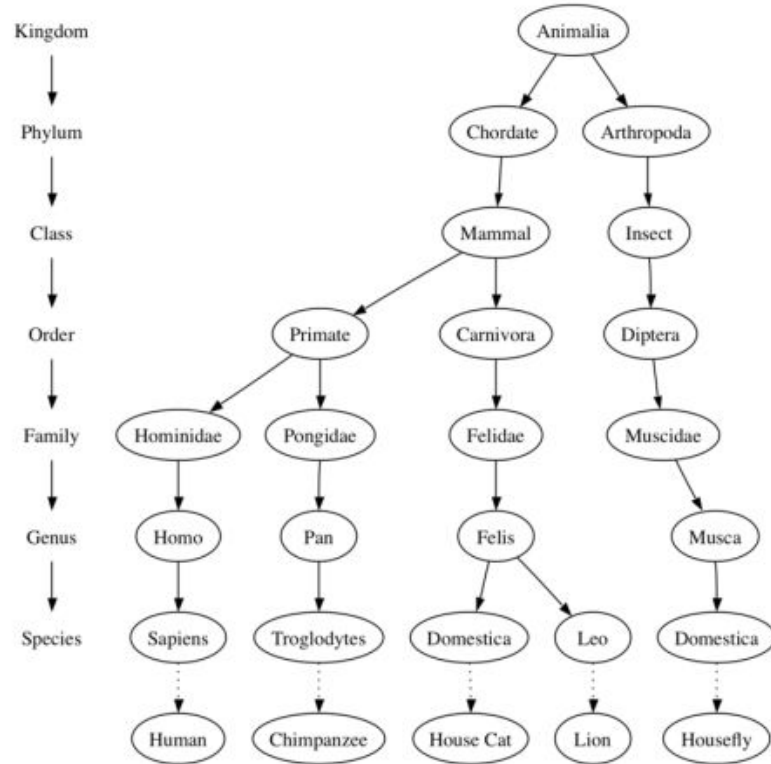
Trees

Luca Bianco - Academic Year 2019-20
luca.bianco@fmach.it
[credits: thanks to Prof. Alberto Montresor]

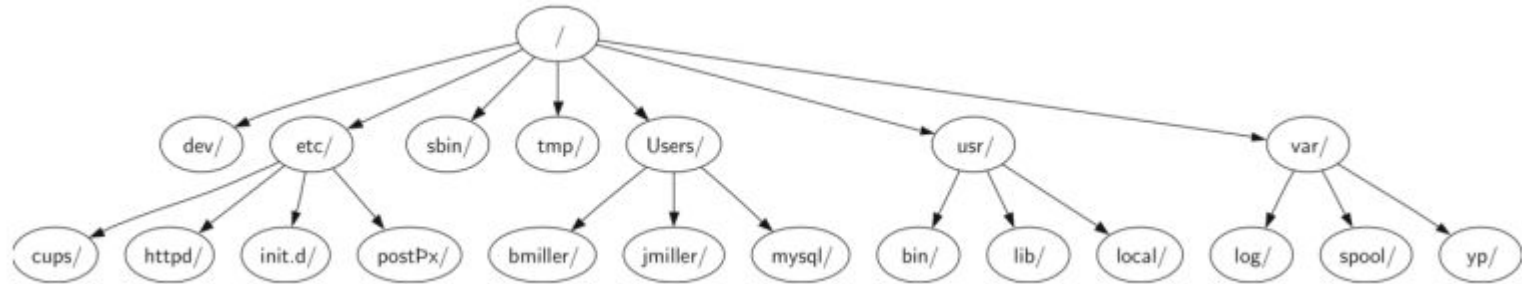
Tree: examples



Tree: examples

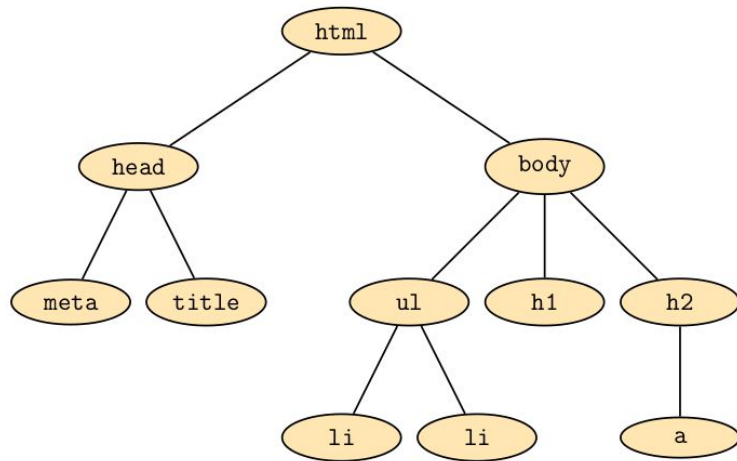


Tree: examples



Tree: examples

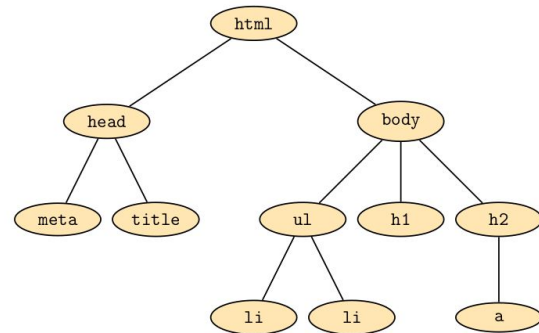
```
<html>
<head>
  <meta http-equiv="Content-Type" content="text/html" />
  <title>simple</title>
</head>
<body>
<h1>A simple web page</h1>
<ul>
  <li>List item one</li>
  <li>List item two</li>
</ul>
<h2><a href="http://www.cs.luther.edu">Luther CS </a></h2>
</body>
</html>
```



Definitions

Trees are data structures composed of two elements: **nodes** and **edges**.

Nodes represent **things** and edges represent **relationships** (typically non-symmetric) among **two** nodes.

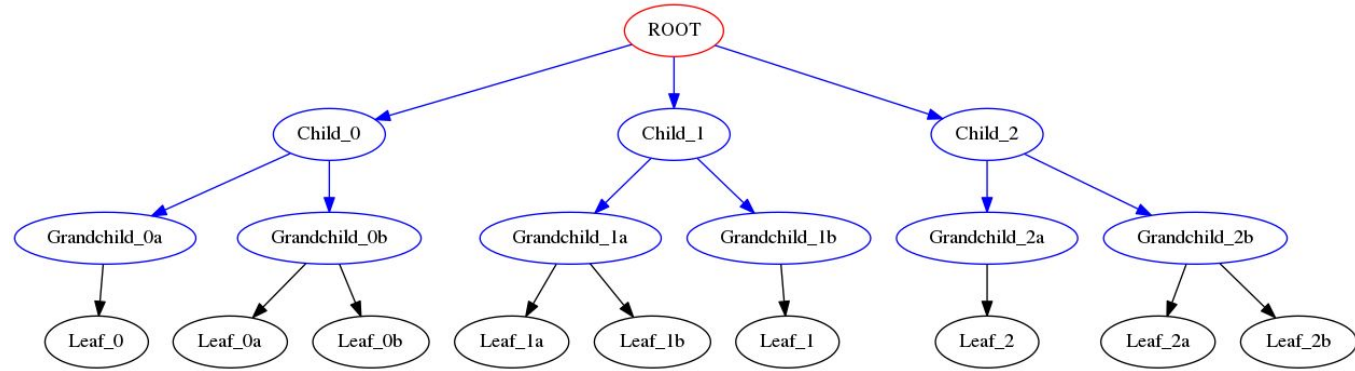


Tree

A tree consists of a set of nodes and a set of edges that connect pairs of nodes, with the following properties:

- One node of the tree is designated as the **root** node
- Every node n , except the root node, is connected by an edge from exactly one other node p
- A unique path traverses from the root to each node
- The tree is connected

Definitions



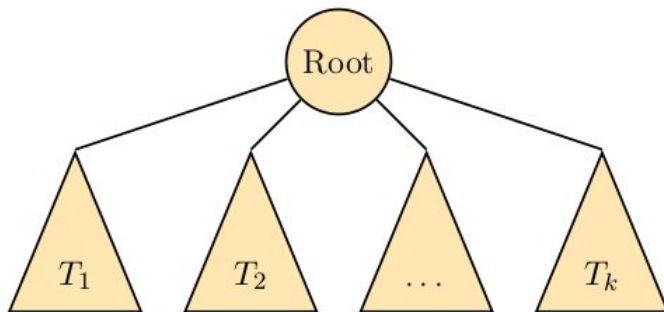
Facts

- One node called the **root** is the top level of the tree and is connected to one or more other nodes;
- If the root is connected to another node by means of one edge, then it is said to be the **parent** of the node (and that node is the **child** of the root);
- Any node can be **parent** of one or more other nodes, the only important thing is that **all nodes have only one parent**;
- The **root is the only exception as it does not have any parent**. Some nodes do not have children and they are called **leaves**;

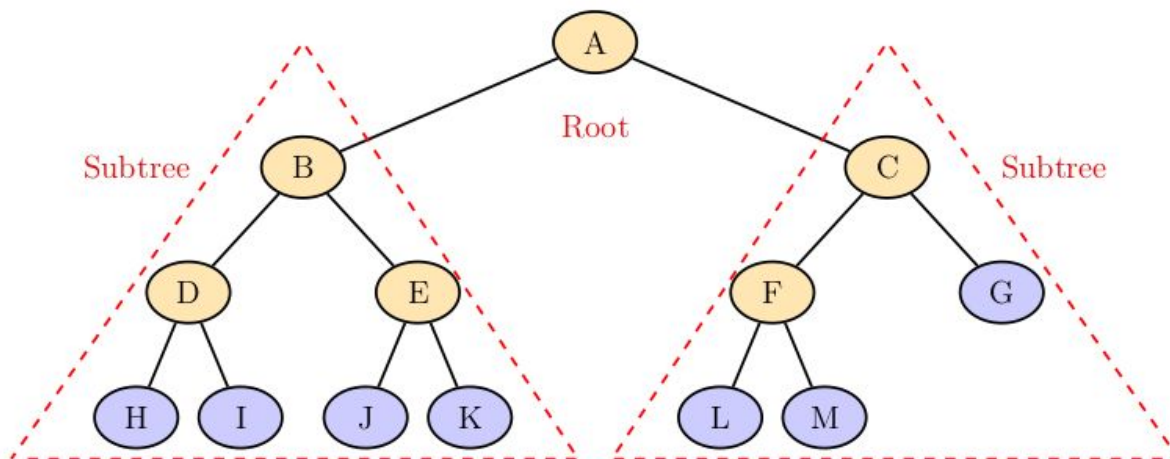
Recursive definition

Tree

A tree is either empty or consists of a root and zero or more subtrees, each of which is also a tree. The root of each subtree is connected to the root of the parent tree by an edge.



Terminology



- A is the tree **root**
- B, C are roots of their subtrees
- D, E are **siblings**
- D, E are **children** of B
- B is the **parent** of D, E
- Purple nodes are **leaves**
- The other nodes are **internal nodes**

Terminology - 2

Depth of a node

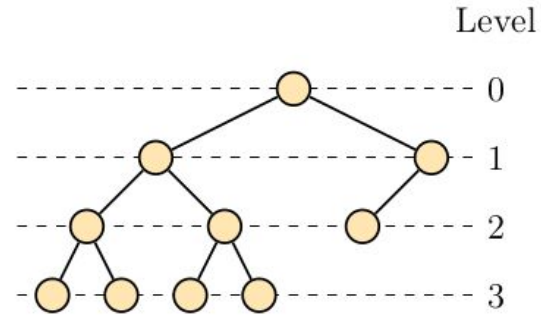
The length of the simple path from the root to the node (measured in number of edges)

Level

The set of nodes having the same depth

Height of the tree

The maximum depth of all its leaves



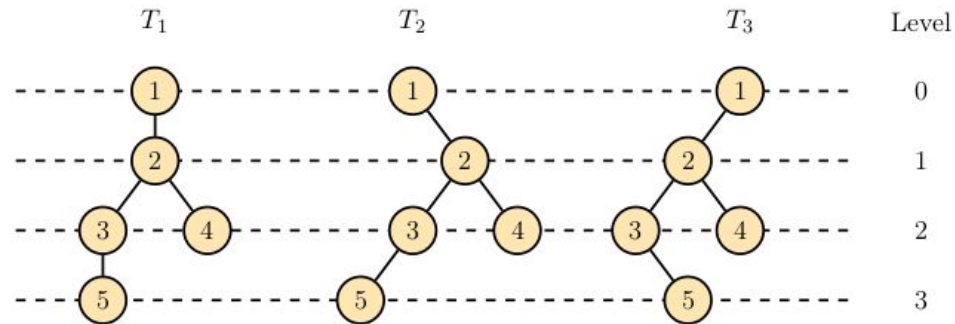
Height of this tree = 3

Binary tree

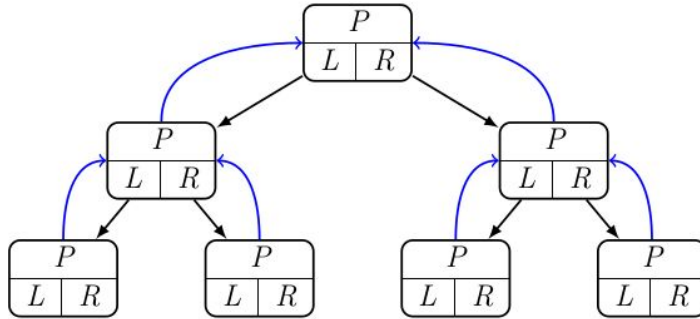
Binary tree

A **binary tree** is a tree data structure in which each node has at most two children, which are referred to as the **left** child and the **right** child.

Note: Two trees T and U having the same nodes, the same children for each node and the same root, are said to be different if a node u is a left child of a node v in T and a right child of the same node in U .



Binary tree: Node



- *parent*: reference to the parent node
- *left*: reference to the left child
- *right*: reference to the right child

When implementing a tree we can define a **node object** and then a **tree object** that stores nodes.

We will use the more compact way which is to **use the recursive definition of a tree**.

Binary tree: ADT

TREE

% Build a new node, initially containing v , with no children or parent

Tree(OBJECT v)

% Read the value stored in this node

OBJECT getValue()

% Write the value stored in this node

setValue(OBJECT v)

% Return the parent, or **none** if this node is the root

TREE getParent()

% Return the left (right) child of this node; return **none** if absent

TREE getLeft()

TREE getRight()

% Insert the subtree rooted in t as left (right) child of this node

insertLeft(TREE t)

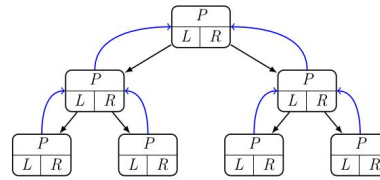
insertRight(TREE t)

% Delete the subtree rooted on the left (right) child of this node

deleteLeft()

deleteRight()

Binary tree: the code



```
class BinaryTree:
    #the initializer, set the data
    #all pointers empty
    def __init__(self, value):
        self.__data = value
        self.__right = None
        self.__left = None
        self.__parent = None

    #returns the value
    def getValue(self):
        return self.__data

    #sets the value
    def setValue(self, newval):
        self.__data = newval

    #gets the parent
    def getParent(self):
        return self.__parent

    #sets the parent
    #NOTE: needed because we are using
    #private attributes
    def setParent(self, tree):
        self.__parent = tree
```

```
#gets the right child
def getRight(self):
    return self.__right

#gets the left child
def getLeft(self):
    return self.__left

#set the right child
def insertRight(self, tree):
    if self.__right == None:
        self.__right = tree
        tree.setParent(self)

#sets the left child
def insertLeft(self, tree):
    if self.__left == None:
        self.__left = tree
        tree.setParent(self)

#deletes the right subtree
def deleteRight(self):
    self.__right = None

#deletes the left subtree
def deleteLeft(self):
    self.__left = None
```

```
TREE
% Build a new node, initially containing v, with no children or
parent
Tree(OBJECT v)

% Read the value stored in this node
OBJECT getValue()

% Write the value stored in this node
setValue(OBJECT v)

% Return the parent, or none if this node is the root
TREE getParent()

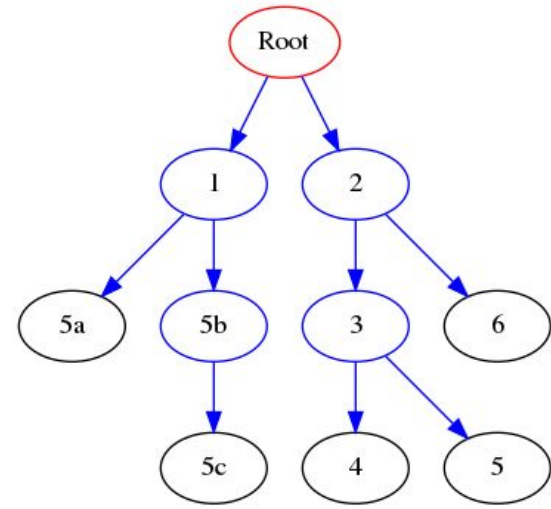
% Return the left (right) child of this node; return none if absent
TREE getLeft()
TREE getRight()

% Insert the subtree rooted in t as left (right) child of this node
insertLeft(TREE t)
insertRight(TREE t)

% Delete the subtree rooted on the left (right) child of this node
deleteLeft()
deleteRight()
```

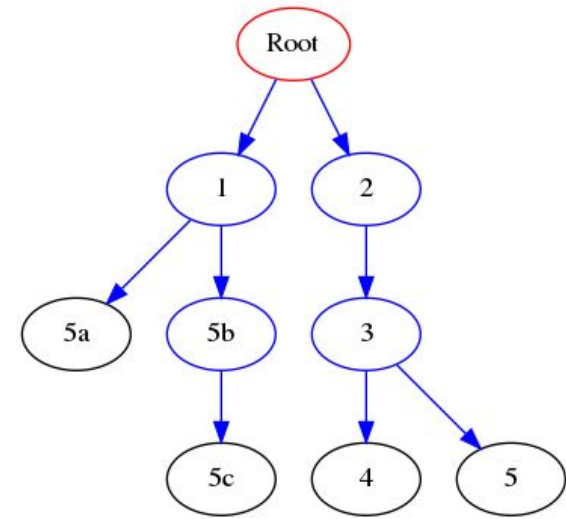
A sample tree...

```
if __name__ == "__main__":  
    BT = BinaryTree("Root")  
    bt1 = BinaryTree(1)  
    bt2 = BinaryTree(2)  
    bt3 = BinaryTree(3)  
    bt4 = BinaryTree(4)  
    bt5 = BinaryTree(5)  
    bt6 = BinaryTree(6)  
    bt5a = BinaryTree("5a")  
    bt5b = BinaryTree("5b")  
    bt5c = BinaryTree("5c")  
  
    BT.insertLeft(bt1)  
    BT.insertRight(bt2)  
    bt2.insertLeft(bt3)  
    bt3.insertLeft(bt4)  
    bt3.insertRight(bt5)  
    bt2.insertRight(bt6)  
    bt1.insertRight(bt5b)  
    bt1.insertLeft(bt5a)  
    bt5b.insertRight(bt5c)
```



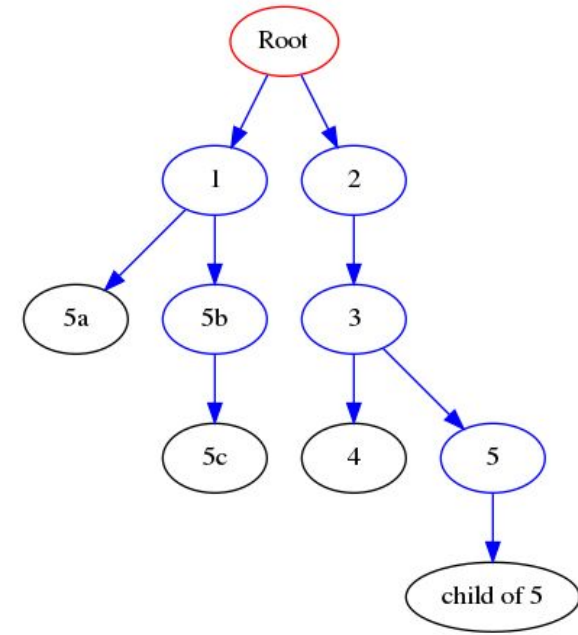
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    bt4 = BinaryTree(4)  
    bt5 = BinaryTree(5)  
    bt6 = BinaryTree(6)  
    bt5a = BinaryTree("5a")  
    bt5b = BinaryTree("5b")  
    bt5c = BinaryTree("5c")  
  
    BT.insertLeft(bt1)  
    BT.insertRight(bt2)  
    bt2.insertLeft(bt3)  
    bt3.insertLeft(bt4)  
    bt3.insertRight(bt5)  
    bt2.insertRight(bt6)  
    bt1.insertRight(bt5b)  
    bt1.insertLeft(bt5a)  
    bt5b.insertRight(bt5c)  
    print("\nDelete right branch of 2")  
    bt2.deleteRight()
```



A sample tree...

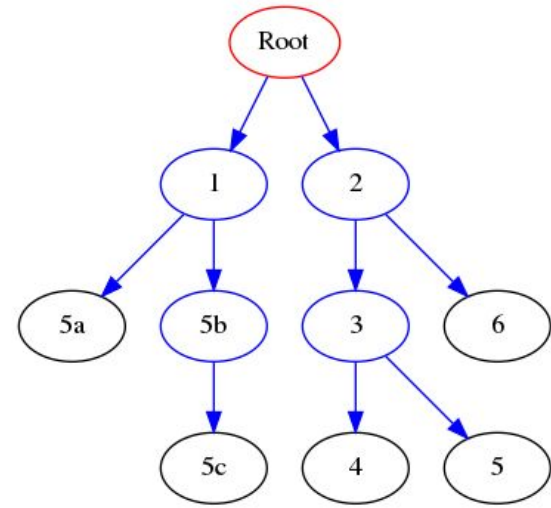
```
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    bt4 = BinaryTree(4)  
    bt5 = BinaryTree(5)  
    bt6 = BinaryTree(6)  
    bt5a = BinaryTree("5a")  
    bt5b = BinaryTree("5b")  
    bt5c = BinaryTree("5c")  
  
    BT.insertLeft(bt1)  
    BT.insertRight(bt2)  
    bt2.insertLeft(bt3)  
    bt3.insertLeft(bt4)  
    bt3.insertRight(bt5)  
    bt2.insertRight(bt6)  
    bt1.insertRight(bt5b)  
    bt1.insertLeft(bt5a)  
    bt5b.insertRight(bt5c)  
    print("\nDelete right branch of 2")  
    bt2.deleteRight()
```



A sample tree...

```
if __name__ == "__main__":
    BT = BinaryTree("Root")
    bt1 = BinaryTree(1)
    bt2 = BinaryTree(2)
    bt3 = BinaryTree(3)
    bt4 = BinaryTree(4)
    bt5 = BinaryTree(5)
    bt6 = BinaryTree(6)
    bt5a = BinaryTree("5a")
    bt5b = BinaryTree("5b")
    bt5c = BinaryTree("5c")

    BT.insertLeft(bt1)
    BT.insertRight(bt2)
    bt2.insertLeft(bt3)
    bt3.insertLeft(bt4)
    bt3.insertRight(bt5)
    bt2.insertRight(bt6)
    bt1.insertRight(bt5b)
    bt1.insertLeft(bt5a)
    bt5b.insertRight(bt5c)
```



Exercise. write a print function that gets the root node and prints the tree:

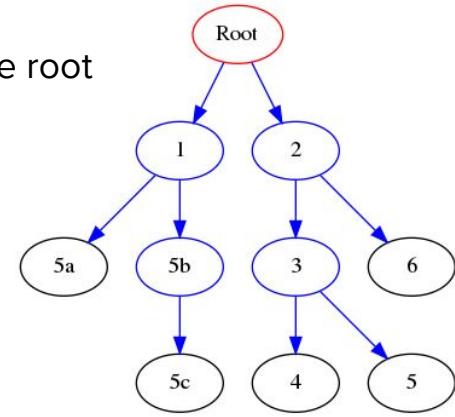
```
Root (r)-> 2
Root (l)-> 1
    1 (r)-> 5b
    1 (l)-> 5a
        5b (r)-> 5c
    2 (r)-> 6
    2 (l)-> 3
        3 (r)-> 5
        3 (l)-> 4
```

A sample tree...

Exercise. write a print function that gets the root node and prints the tree:

Tabs depend
on depth

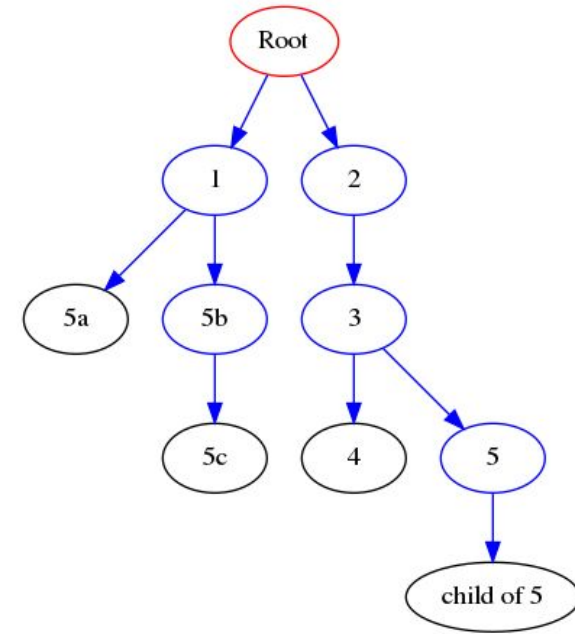
```
Root (r)-> 2
Root (l)-> 1
  1 (r)-> 5b
  1 (l)-> 5a
    5b (r)-> 5c
    2 (r)-> 6
    2 (l)-> 3
      3 (r)-> 5
      3 (l)-> 4
```



```
def printTree(root):
    cur = root
    #each element is a node and a depth
    #depth is used to format prints (with tabs)
    nodes = [(cur,0)]
    tabs = ""
    lev = 0
    while len(nodes) > 0:
        cur, lev = nodes.pop(-1)
        if cur.getRight() != None:
            print("{}{} (r)-> {}".format("\t"*lev,
                                           cur.getValue(),
                                           cur.getRight().getValue()))
            nodes.append((cur.getRight(), lev+1))
        if cur.getLeft() != None:
            print("{}{} (l)-> {}".format("\t"*lev,
                                           cur.getValue(),
                                           cur.getLeft().getValue()))
            nodes.append((cur.getLeft(), lev+1))
```

A sample tree...

```
def printTree(root):
    cur = root
    #each element is a node and a depth
    #depth is used to format prints (with tabs)
    nodes = [(cur,0)]
    tabs = ""
    lev = 0
    while len(nodes) > 0:
        cur, lev = nodes.pop(-1)
        if cur.getRight() != None:
            print("{}{} (r)-> {}".format("\t"*lev,
                                           cur.getValue(),
                                           cur.getRight().getValue()))
            nodes.append((cur.getRight(), lev+1))
        if cur.getLeft() != None:
            print("{}{} (l)-> {}".format("\t"*lev,
                                           cur.getValue(),
                                           cur.getLeft().getValue()))
            nodes.append((cur.getLeft(), lev+1))
```



OUTPUT

```
Root (r)-> 2
Root (l)-> 1
    1 (r)-> 5b
    1 (l)-> 5a
        5b (r)-> 5c
    2 (l)-> 3
        3 (r)-> 5
        3 (l)-> 4
            5 (l)-> child of 5
```

Tree traversals

Tree traversal / search

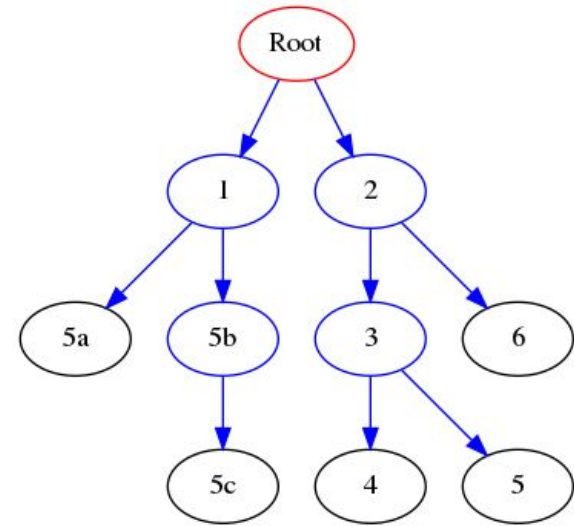
A strategy to pass through (visit) all the nodes of a tree.

Depth-First Search (DFS)

- Each **subtree** of the tree is visited, one after another
- Three variants (pre/in/post order)
- Requires a **stack**



To store all unfinished calls to DFS(node)



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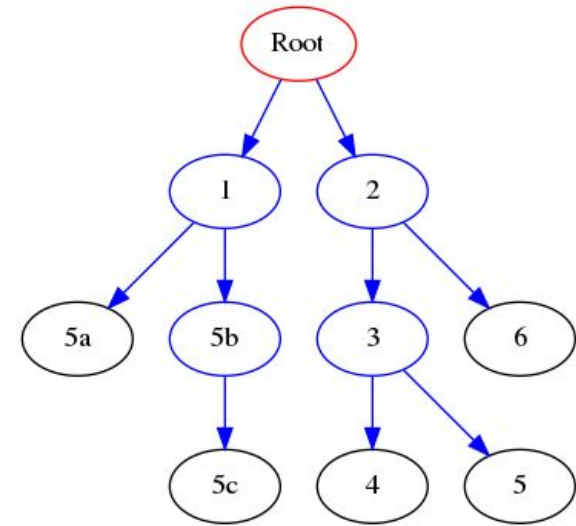
To store all unfinished calls to DFS(node)

Recursively

1. visit Root
2. visit left
3. visit right



Preorder:
Root



Tree traversals

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Recursively

1. visit Root
2. visit left
3. visit right



Preorder:

Root
1

Stack: (5c right of 5b!)

1
Root



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Recursively

1. visit Root
2. visit left
3. visit right



Preorder:

Root
1
5a

Stack: (5c right of 5b!)

5a
1
Root



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Recursively

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2. visit left
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Preorder:

Root
1
5a

Stack: (5c right of 5b!)

1
Root



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Tree traversal / search

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Recursively

1. visit Root
2. visit left
3. visit right



Preorder:

Root
1
5a
5b

Stack: (5c right of 5b!)

5b
1
Root



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Recursively

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3. visit right



Preorder:

Root
1
5a
5b
5c

Stack: (5c right of 5b!)

5c
5b
1
Root



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Preorder:

Root
1
5a
5b
5c

Stack: (5c right of 5b!)

5b
1
Root



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Stack: (5c right of 5b!)

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5a
5b
5c

Stack: (5c right of 5b!)

Root



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Recursively

1. visit Root
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3. visit right



Preorder:

Root
1
5a
5b
5c
2

Stack: (5c right of 5b!)

2
Root



Tree traversals

Tree traversal / search

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5a
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5c
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3

Stack: (5c right of 5b!)

3
2
Root



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3. visit right



Preorder:

Root
1
5a
5b
5c
2
3
4

Stack: (5c right of 5b!)

4
3
2
Root



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Root
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5a
5b
5c
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4

Stack: (5c right of 5b!)

3
2
Root



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- Each **subtree** of the tree is visited, one after another
- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit Root
2. visit left
3. visit right



Preorder:

Root
1
5a
5b
5c
2
3
4
5

Stack: (5c right of 5b!)

5
3
2
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

Depth-First Search (DFS)

- Each **subtree** of the tree is visited, one after another
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Recursively

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3. visit right

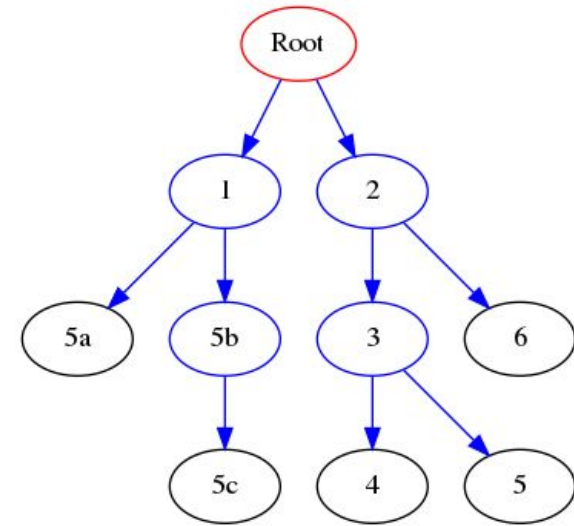


Preorder:

Root
1
5a
5b
5c
2
3
4
5

Stack: (5c right of 5b!)

3
2
Root



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Stack: (5c right of 5b!)

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Root



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Recursively

1. visit Root
2. visit left
3. visit right



Preorder:

Root
1
5a
5b
5c
2
3
4
5
6

Stack: (5c right of 5b!)

6
2
Root



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Tree traversal / search

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Depth-First Search (DFS)

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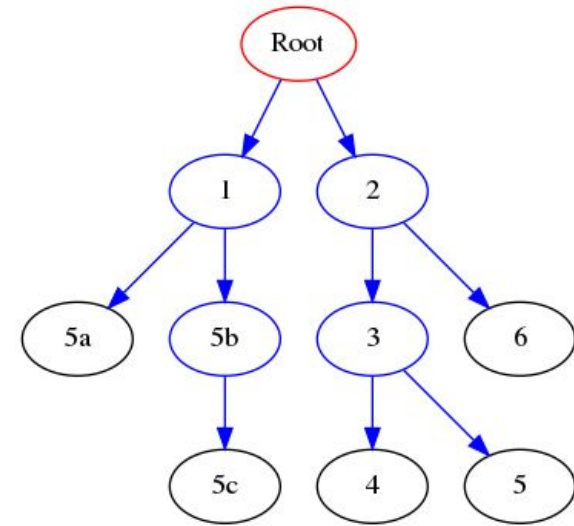


Preorder:

Root
1
5a
5b
5c
2
3
4
5
6

Stack: (5c right of 5b!)

2
Root



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2. visit left
3. visit right

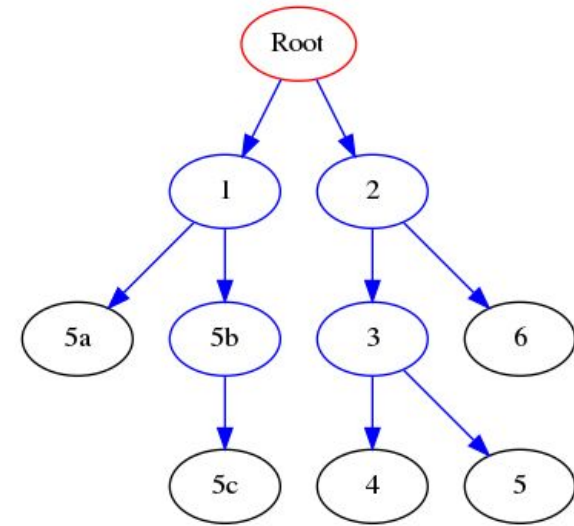


Preorder:

Root
1
5a
5b
5c
2
3
4
5
6

Stack: (5c right of 5b!)

Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

Depth-First Search (DFS)

- Each **subtree** of the tree is visited, one after another
- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit Root
2. visit left
3. visit right



Preorder:

Root
1
5a
5b
5c
2
3
4
5
6

Stack: (5c right of 5b!)

empty! **Done**



Tree traversals

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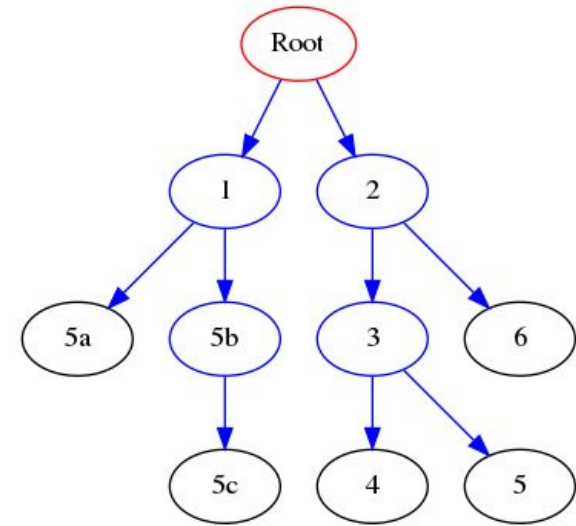
Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

Stack: (5c right of 5b!)
Root



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Recursively

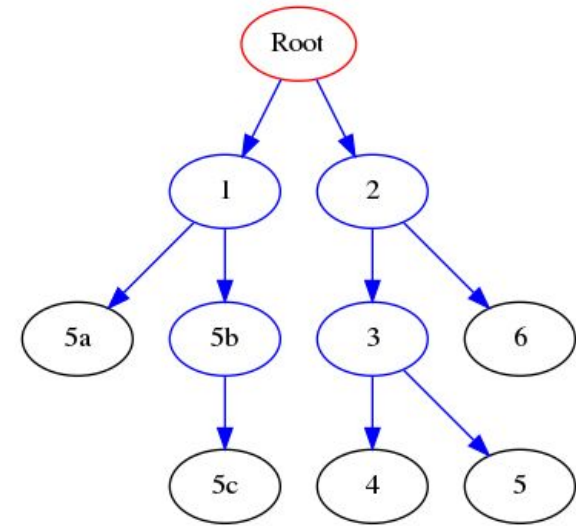
1. visit left
2. visit Root
3. visit right



Inorder:

Stack: (5c right of 5b!)

1
Root



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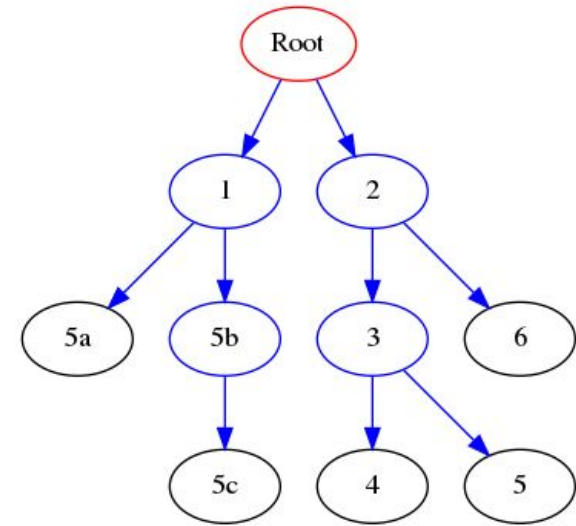
Recursively

1. visit left
2. visit Root
3. visit right



Inorder:
5a

Stack: (5c right of 5b!)
5a
1
Root



Tree traversals

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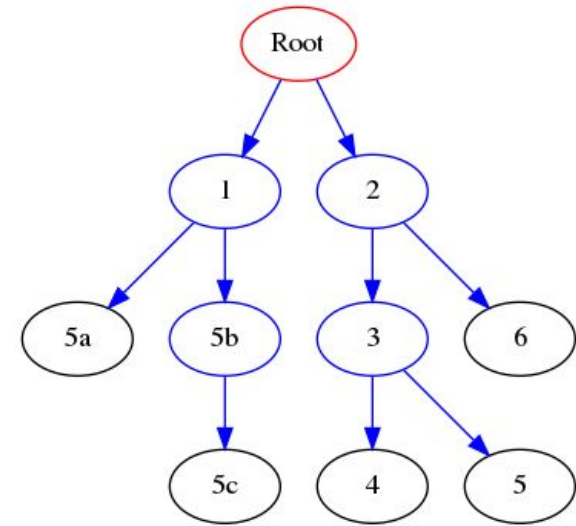
Recursively

1. visit left
2. visit Root
3. visit right



Inorder:
5a

Stack: (5c right of 5b!)
1
Root



Tree traversals

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Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1

Stack: (5c right of 5b!)

1
Root



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- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1

Stack: (5c right of 5b!)

5b
1
Root



Tree traversals

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- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b

Stack: (5c right of 5b!)

5b
1
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

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- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c

Stack: (5c right of 5b!)

5c
5b
1
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

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- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c

Stack: (5c right of 5b!)

5b
1
Root



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- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c

Stack: (5c right of 5b!)

1
Root



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Inorder:

5a
1
5b
5c

Stack: (5c right of 5b!)

Root



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2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root

Stack: (5c right of 5b!)

Root



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- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root

Stack: (5c right of 5b!)

2
Root



Tree traversals

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- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root

Stack: (5c right of 5b!)

3
2
Root



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- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root
4

Stack: (5c right of 5b!)

4
3
2
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

Depth-First Search (DFS)

- Each **subtree** of the tree is visited, one after another
- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root
4

Stack: (5c right of 5b!)

3
2
Root



Tree traversals

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3. visit right



Inorder:

5a
1
5b
5c
Root
4
3

Stack: (5c right of 5b!)

3
2
Root



Tree traversals

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- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root
4
3
5

Stack: (5c right of 5b!)

5
3
2
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

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- Each **subtree** of the tree is visited, one after another
- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root
4
3
5

Stack: (5c right of 5b!)

3
2
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

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Recursively

1. visit left
2. visit Root
3. visit right

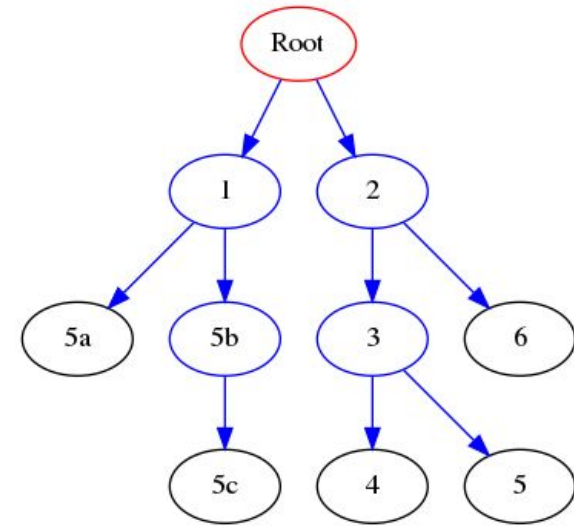


Inorder:

5a
1
5b
5c
Root
4
3
5

Stack: (5c right of 5b!)

2
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

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Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root
4
3
5
2

Stack: (5c right of 5b!)

2
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

Depth-First Search (DFS)

- Each **subtree** of the tree is visited, one after another
- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root
4
3
5
2
6

Stack: (5c right of 5b!)

6
2
Root



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

Depth-First Search (DFS)

- Each **subtree** of the tree is visited, one after another
- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root
4
3
5
2
6

Stack: (5c right of 5b!)

2
Root



Tree traversals

Tree traversal / search

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- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right



Inorder:

5a
1
5b
5c
Root
4
3
5
2
6

Stack: (5c right of 5b!)

Root



Tree traversals

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- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

1. visit left
2. visit Root
3. visit right

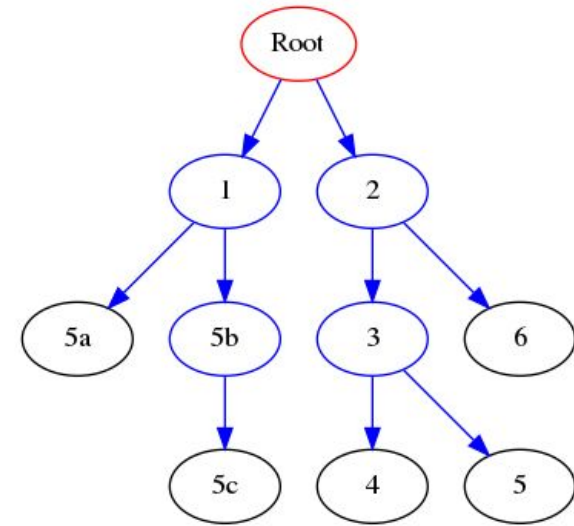


Inorder:

5a
1
5b
5c
Root
4
3
5
2
6

Stack: (5c right of 5b!)

empty. Done!



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

Depth-First Search (DFS)

- Each **subtree** of the tree is visited, one after another
- Three variants (pre/in/post order)
- Requires a **stack**

Recursively

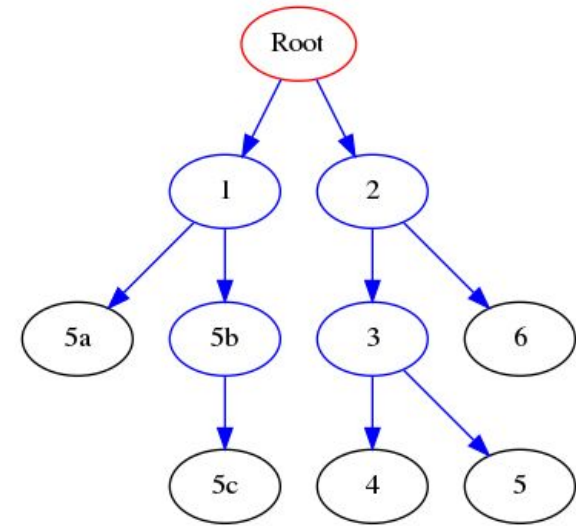
1. visit left
2. visit right
3. visit Root



Postorder:

5a
5c (right of 5b)
5b
1
4
5
3
6
2
Root

Stack: Exercise!



DFS: the code

visit means “print”

```
def DFS(node, kind = "preorder"):
    if node != None:
        if kind == "preorder":
            print("{}".format(node.getValue()))
            DFS(node.getLeft(), kind = kind)
        if kind == "inorder":
            print("{}".format(node.getValue()))
            DFS(node.getRight(), kind = kind)
        if kind == "postorder":
            print("{}".format(node.getValue()))
```

implicit
stack

Preorder:

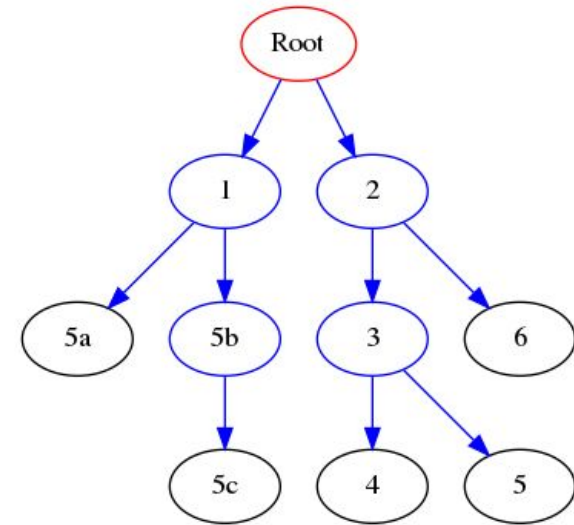
Root
1
5a
5b
5c
2
3
4
5
6

Inorder:

5a
1
5b
5c
Root
4
4
3
5
2
6

Postorder:

5a
5c
5b
1
4
5
3
6
2
Root



Tree traversals

Tree traversal / search

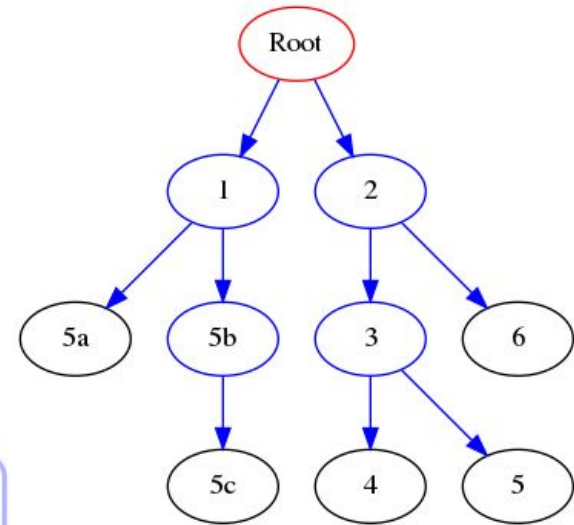
A strategy to pass through (visit) all the nodes of a tree.

Depth-First Search (DFS)

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Breadth-First Search (BFS)

- Each **level** of the tree is visited, one after the other
- Starts from the root
- Requires a **queue**



Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

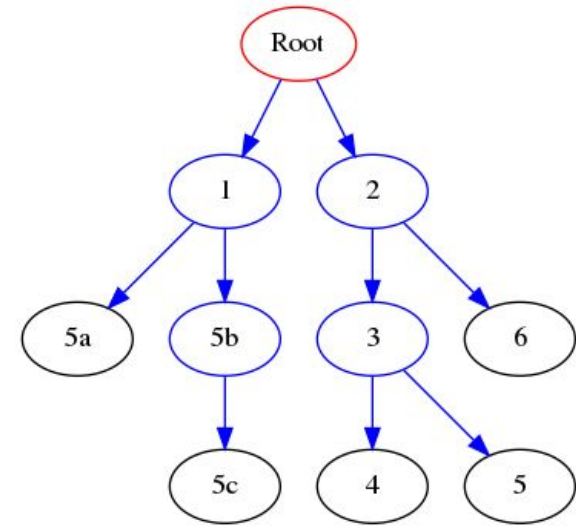
Breadth-First Search (BFS)

- Each **level** of the tree is visited, one after the other
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- Requires a **queue**

0. Add root to the queue Q

Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Queue
Root

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

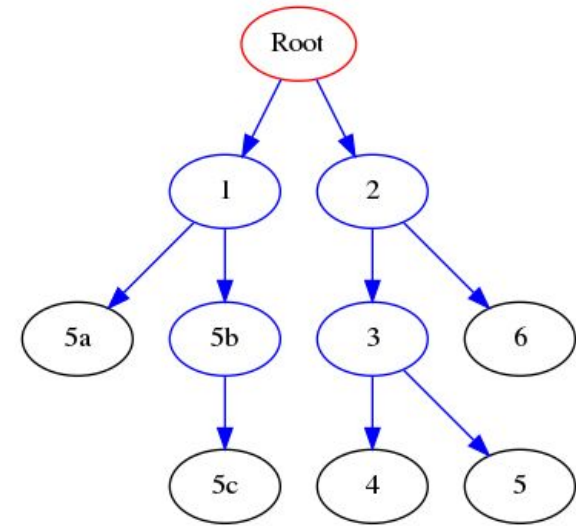
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- Starts from the root
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0. Add root to the queue Q

Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order
Root

Queue
1, 2

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

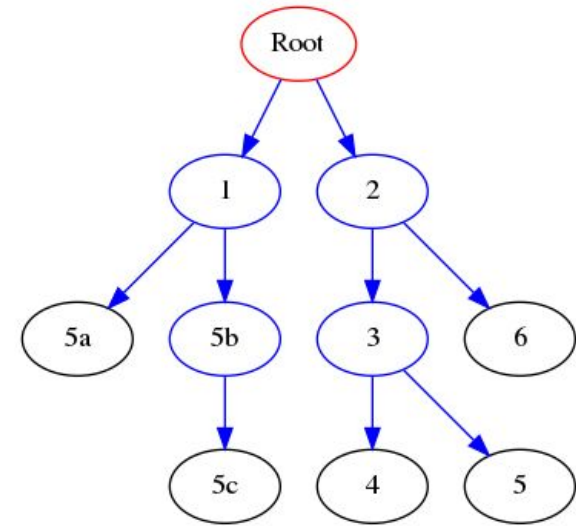
Breadth-First Search (BFS)

- Each **level** of the tree is visited, one after the other
- Starts from the root
- Requires a **queue**

0. Add root to the queue Q

Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Root
1

Queue

2, 5a, 5b

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

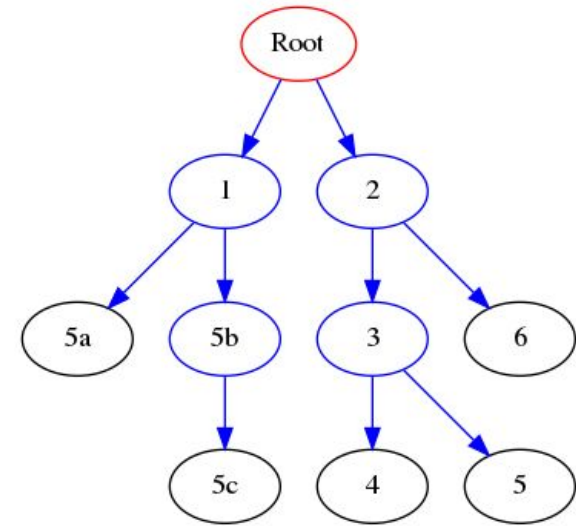
Breadth-First Search (BFS)

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- Requires a **queue**

0. Add root to the queue Q

Recursively

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2. visit the node
3. add all children to Q



Visit order

Root
1
2

Queue

5a, 5b, 3, 6

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

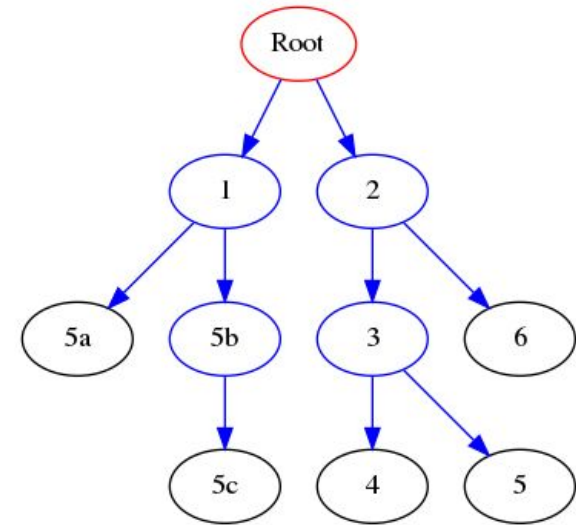
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Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Root
1
2
5a

Queue

5b, 3, 6

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

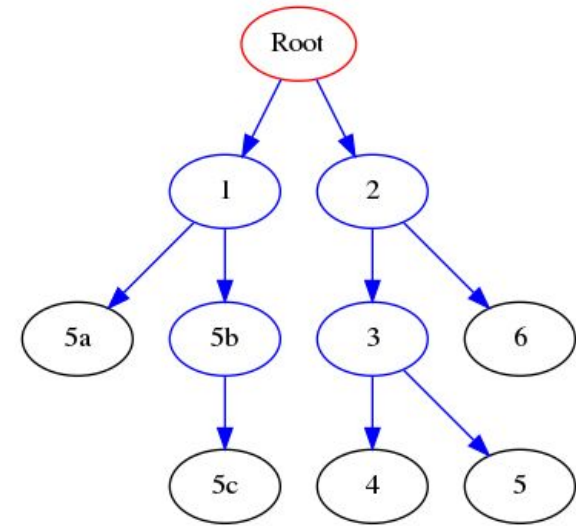
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Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Root
1
2
5a
5b

Queue

3, 6, 5c

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

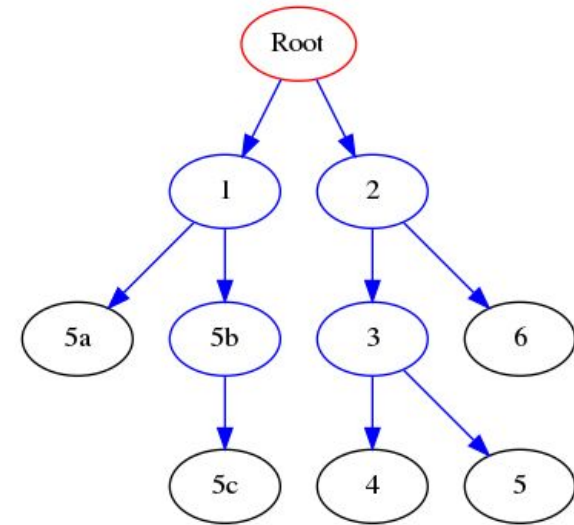
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- Starts from the root
- Requires a **queue**

0. Add root to the queue Q

Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Root
1
2
5a
5b
3

Queue

6, 5c, 4, 5

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

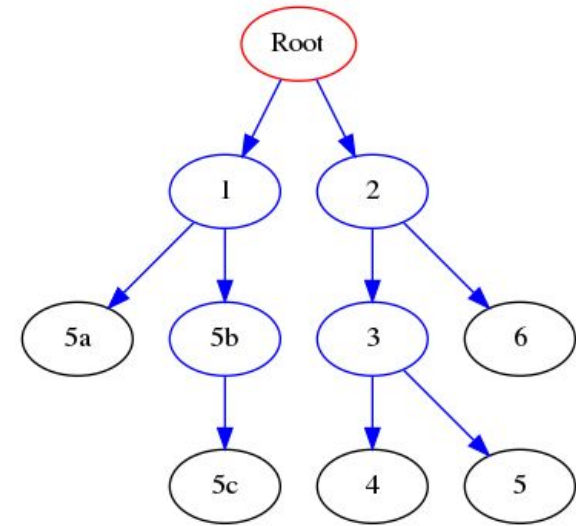
Breadth-First Search (BFS)

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- Starts from the root
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0. Add root to the queue Q

Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Root
1
2
5a
5b
3
6

Queue

5c, 4, 5

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

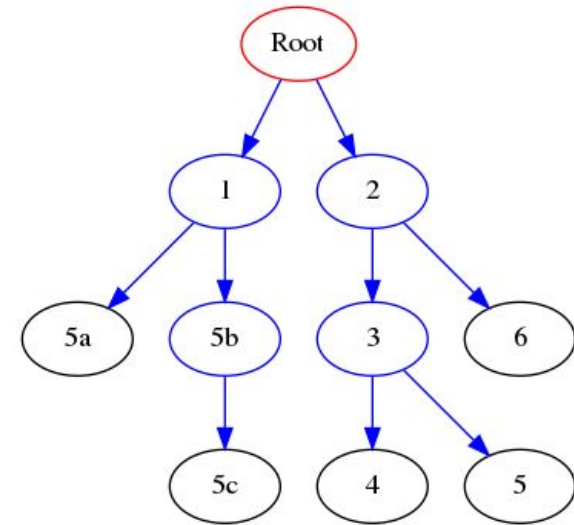
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0. Add root to the queue Q

Recursively

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2. visit the node
3. add all children to Q



Visit order

Root
1
2
5a
5b
3
6
5c

Queue

4, 5

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

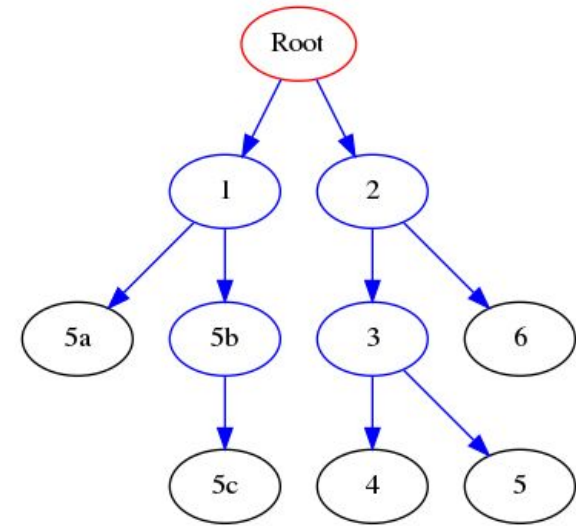
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0. Add root to the queue Q

Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Root
1
2
5a
5b
3
6
5c
4

Queue

5

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

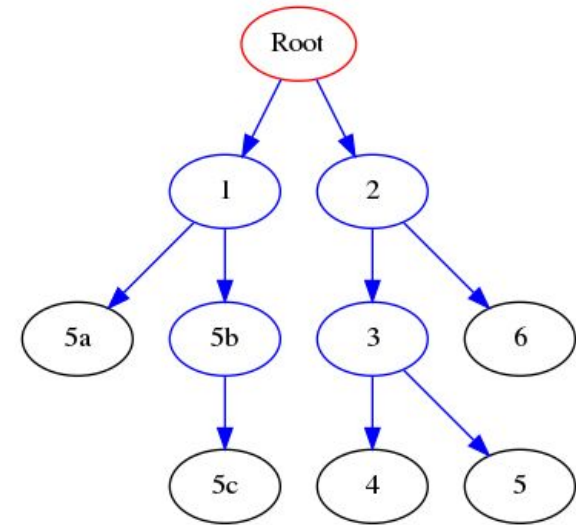
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- Starts from the root
- Requires a **queue**

0. Add root to the queue Q

Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Root
1
2
5a
5b
3
6
5c
4
5

Queue

Empty. Done

Tree traversals

Tree traversal / search

A strategy to pass through (visit) all the nodes of a tree.

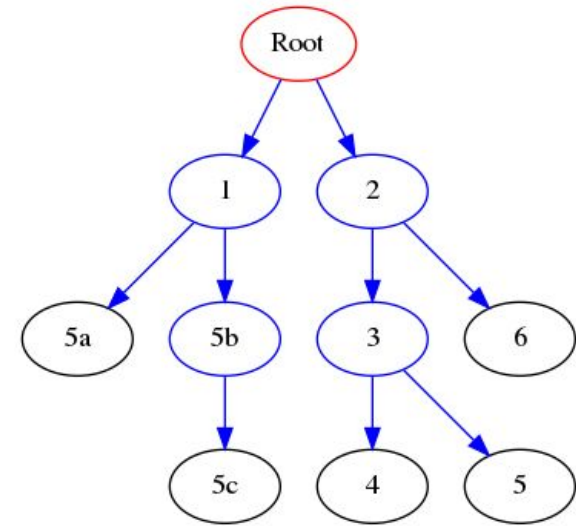
Breadth-First Search (BFS)

- Each **level** of the tree is visited, one after the other
- Starts from the root
- Requires a **queue**

0. Add root to the queue Q

Recursively

1. get node from Q
2. visit the node
3. add all children to Q



Visit order

Root
1
2
5a
5b
3
6
5c
4
5

Level

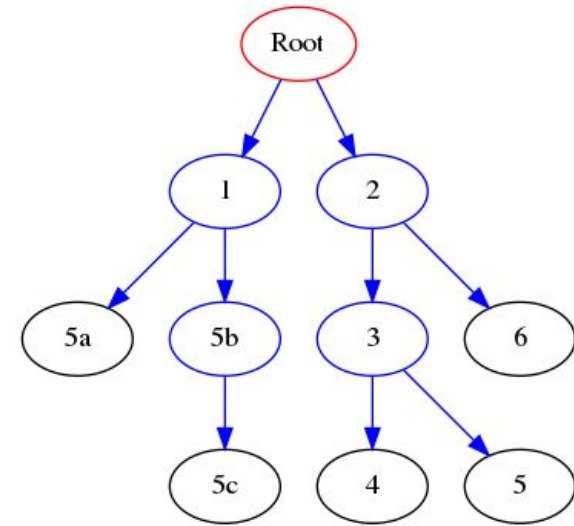
0
1
1
2
2
2
2
3
3
3

Tree traversals: BFS

```
from collections import deque

def BFS(node):
    Q = deque()
    if node != None:
        Q.append(node)

    while len(Q) > 0:
        curNode = Q.popleft()
        if curNode != None:
            print("{}".format(curNode.getValue()))
            Q.append(curNode.getLeft())
            Q.append(curNode.getRight())
```

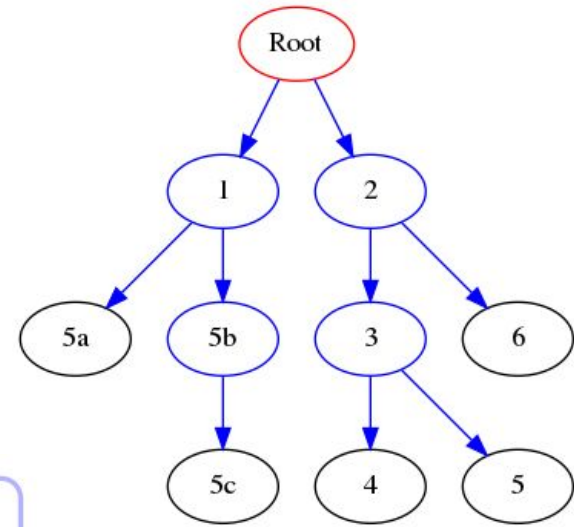


BFS visit:

Root
1
2
5a
5b
3
6
5c
4
5

Tree traversals: complexity

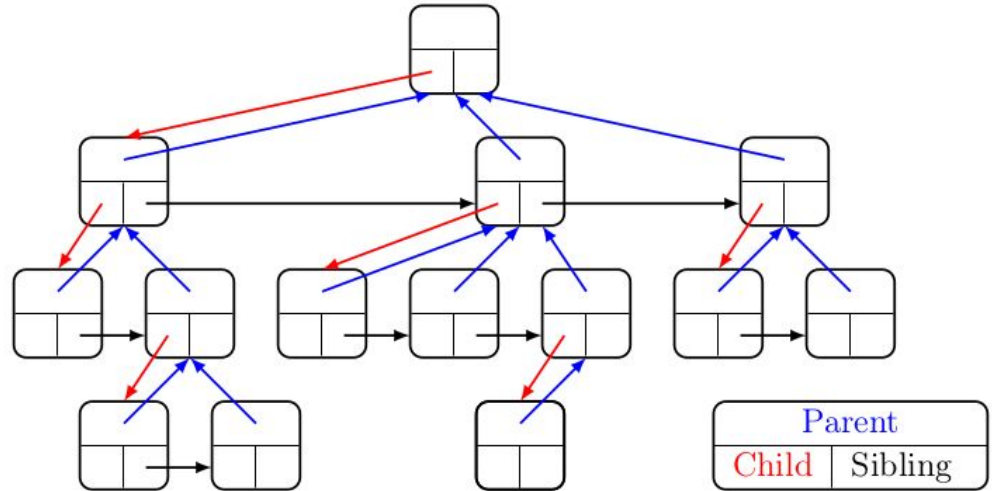
The cost of a visit of a tree containing n nodes is $\Theta(n)$, because each node is visited exactly once.



Generic trees

Generic Trees are like binary trees, but **each node can have more than 2 children**. One possible implementation is that each node (that is a subtree in itself) has a **value**, a link to its **parent** and a **list of children**.

Another implementation is that each node has a **value**, a link to its **parent**, a link to its **next sibling** and a link to its **first child**.



Generic trees

TREE

% Build a new node, initially containing v , with no children or parent

Tree(OBJECT v)

% Read the value stored in nodes

OBJECT `getValue()`

% Write the value stored in nodes

`setValue(OBJECT v)`

% Returns the parent, or `None` if this node is root

TREE `getParent()`

% Returns the first child, or `None` if this node is leaf

TREE `leftmostChild()`

% Returns the next sibling, or `None` if there is none

TREE `rightSibling()`

% Insert the subtree t as first child of this node

`insertChild(TREE t)`

% Insert the subtree t as next sibling of this node

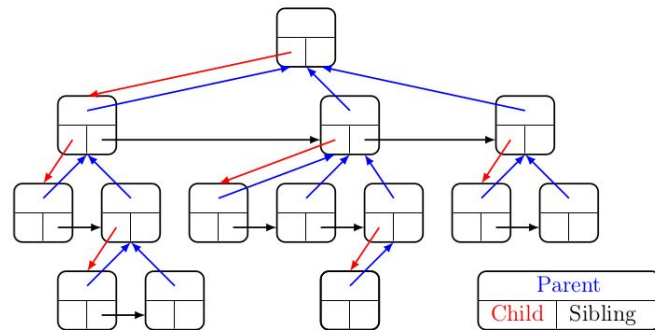
`insertSibling(TREE t)`

% Destroy the subtree rooted in the first child

`deleteChild()`

% Destroy the subtree rooted in the next sibling

`deleteSibling()`



Exercise!

Exercise

The visit order of a binary tree containing 9 nodes are the following:

- A, E, B, F, G, C, D, I, H (pre-order) Root-Left-Right
- B, G, C, F, E, H, I, D, A (post-order) Left-Right-Root
- B, E, G, F, C, A, D, H, I (in-order) Left-Root-Right

What is the corresponding binary tree? Explain.

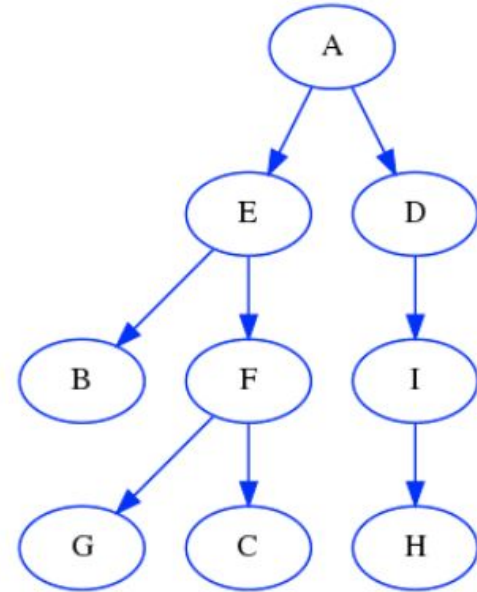
Exercise

The visit order of a binary tree containing 9 nodes are the following:

- A, E, B, F, G, C, D, I, H (pre-order)
- B, G, C, F, E, H, I, D, A (post-order)
- B, E, G, F, C, A, D, H, I (in-order)

What is the corresponding binary tree? Explain.

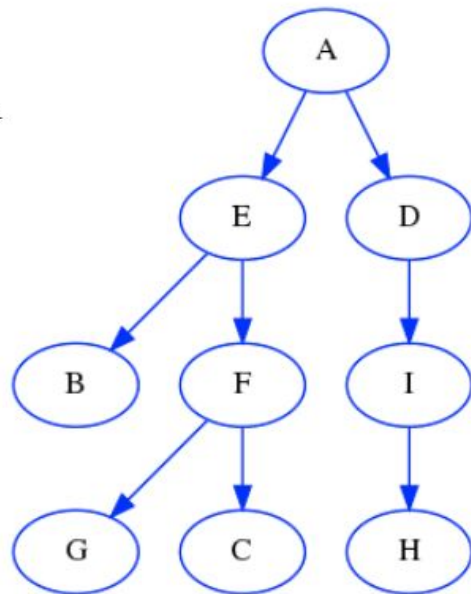
Preorder visit	Postorder visit	Inorder visit
A	B	B
E	G	E
B	C	G
F	F	F
G	E	C
C	H	A
D	I	D
I	D	H
H	A	I



where I is on the right of D and H is on the left of I

Exercises

- The width of a binary tree is the largest number of nodes that belong to the same level. Write a function that given a tree t , returns the width of t .
- The minimal height of a binary tree t is the minimal distance between node v and any of the leaf in its subtree. Write a function that given a tree t , returns the minimal height of t .
- Write a function that given a binary tree t and an integer k , returns the number of nodes at level k



Width: 3

Minimal height: 2

$k = 2 \rightarrow$ output: 3