



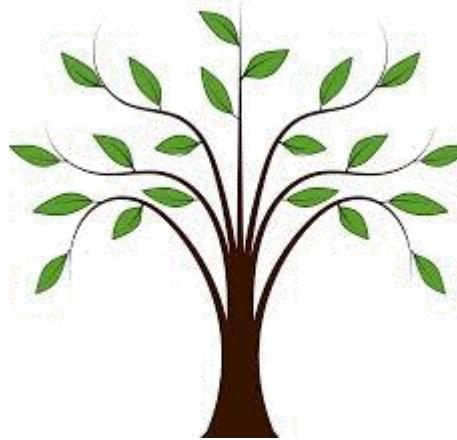
This Photo

Tree

1. Tree Definitions

2. Binary Tree

- Traversals
- Binary Search Tree
- Representations
- Application : Expression Tree



- 3. AVL Tree
- 4. Which Representations ?
- 5. n-ary Tree
- 6. Generic Tree
- 7. Multiway Search Tree
- 8. B-Trees

Tree Definitions

A tree อาจ

1. empty ไม่มี nodes เรียก null tree / empty tree

หน้า ๑

- ## 2. ประกอนด้วย

1. root node

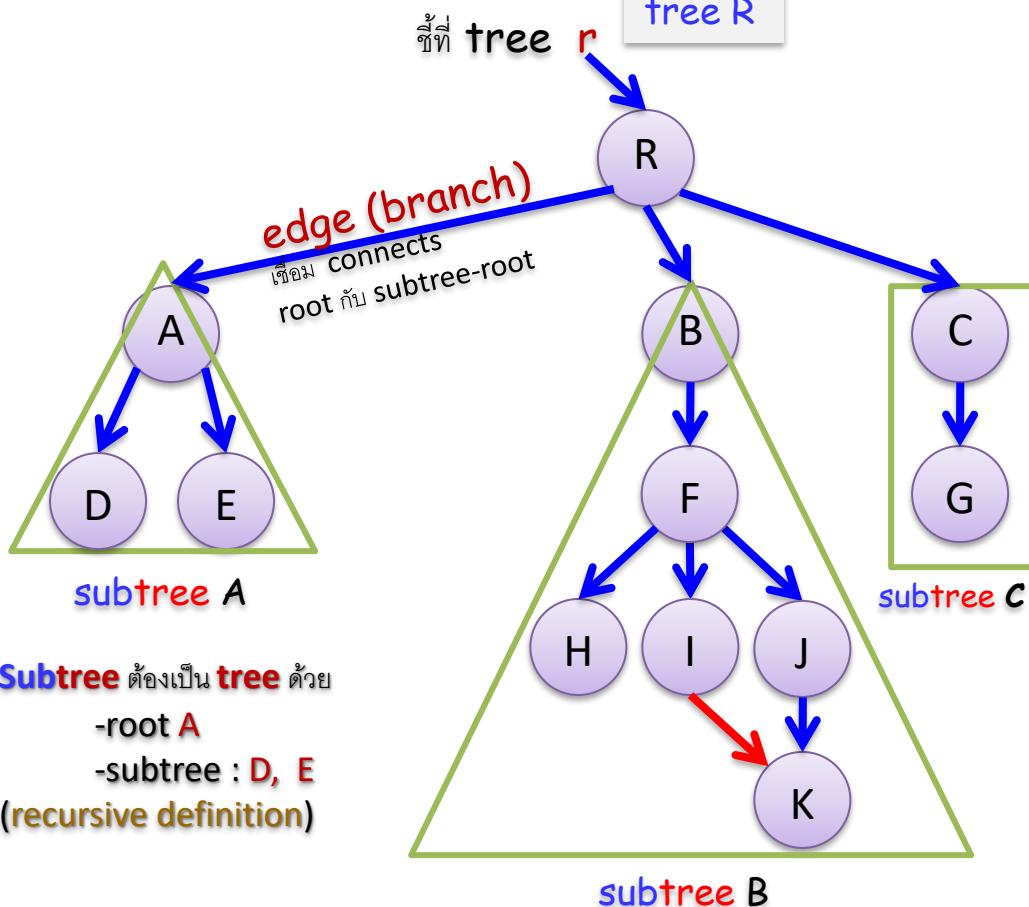
2. ≥ 0 subtrees

Node ใน tree ต้อง disjoint กัน

ต้องไม่มี node ร่วมกันใน root หรือใน subtrees



ชื่อของ tree นิยมเรียกตาม root



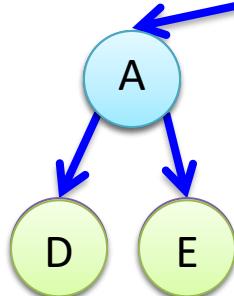
K ไม่ disjoint (อยู่ในทั้ง subtree I & subtree J) → R ไม่ใช่ tree

ใน tree : branches ไม่เชื่อมเป็นวง

Tree Definitions

Root = **father (parent)** of subtree's root.
= **father** ของ root ของ subtree

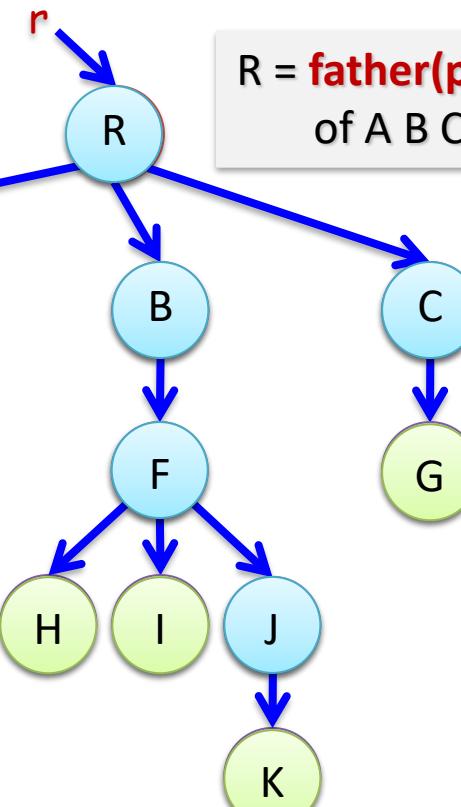
Subtree's root (root ของ subtree)
= **son (child)** of his father.
= **son (child)** ของพ่อของมัน



Leaf (leave) = External node.

Leaf (leave) ≠ Internal node.

Root ไม่มีพ่อ



R = **father(parent)**
of A B C

A B C = **sons(childs)**
of R

Father of F ?
Sons of A ?
Father of R ?
Sons of H ?

Leaf (leave)
= node with no son.
= node ที่ไม่มีลูก



Siblings	Leaf Grand Parent	Internal Grand Child
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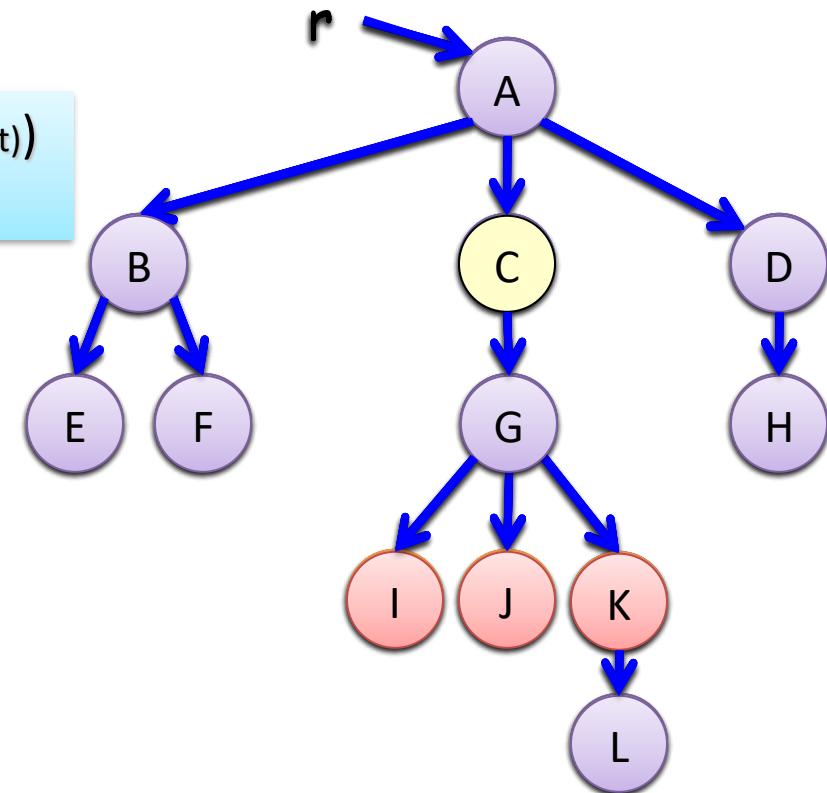
Leaf node (external, outer, terminal)
node with no son

Branch node (internal, inner, inode (for short))
node \neq leaf

Brothers (siblings)
node with same father

Grand Parent
father of father

Grand Child
son of son



Path, Path Length, Depth, Height

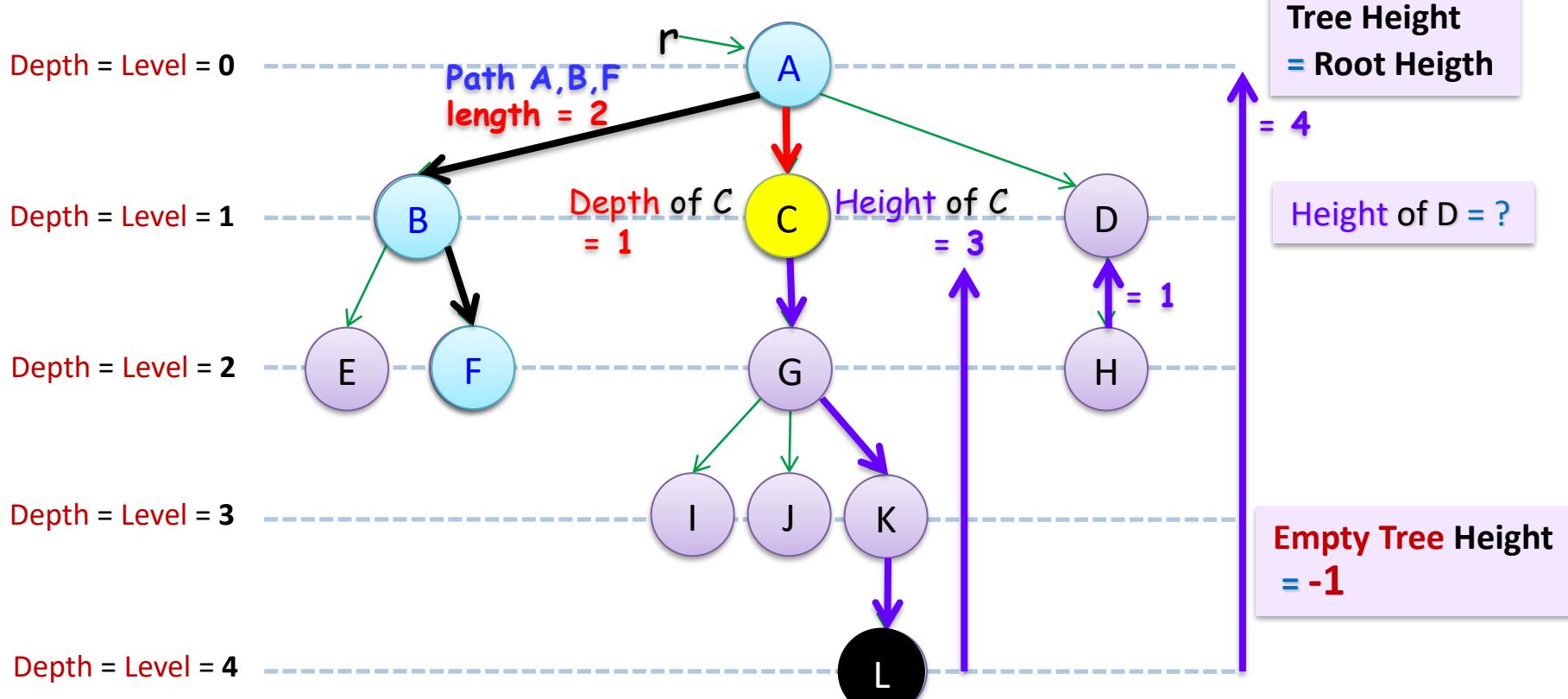
Path (from n to d) sequence of nodes and edges connecting a node n with a descendant d

In tree, only 1 path from node to node

Depth (level) of node = path length from root to node

Height of node = longest path length from node to leaf

Path length = # edge in path



Ancestor & Descendent

Ancestor បរពុទ្ធម៌

father of ancestor

A = ancestor of D

if has path from A to D

Decendent តួកលាន

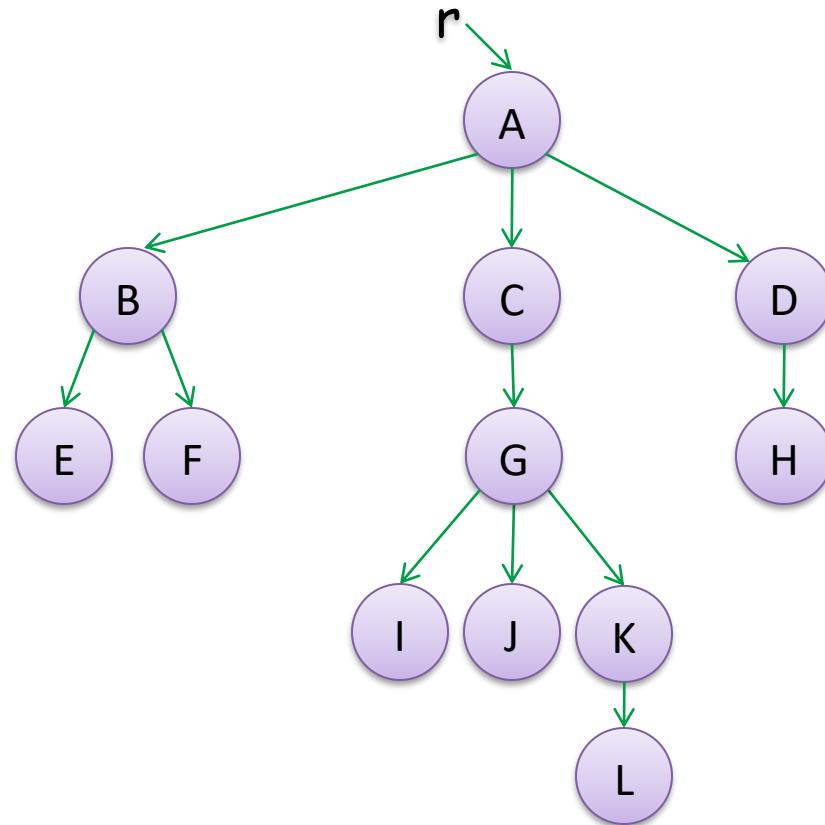
son of decendent

A = Proper Ancestor of D

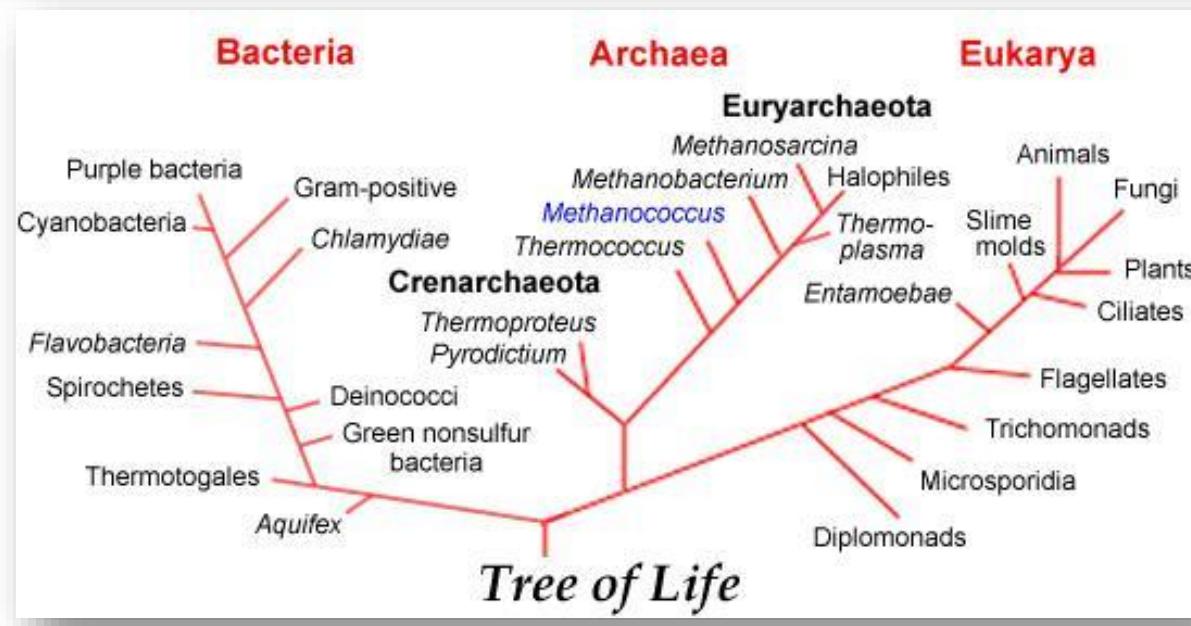
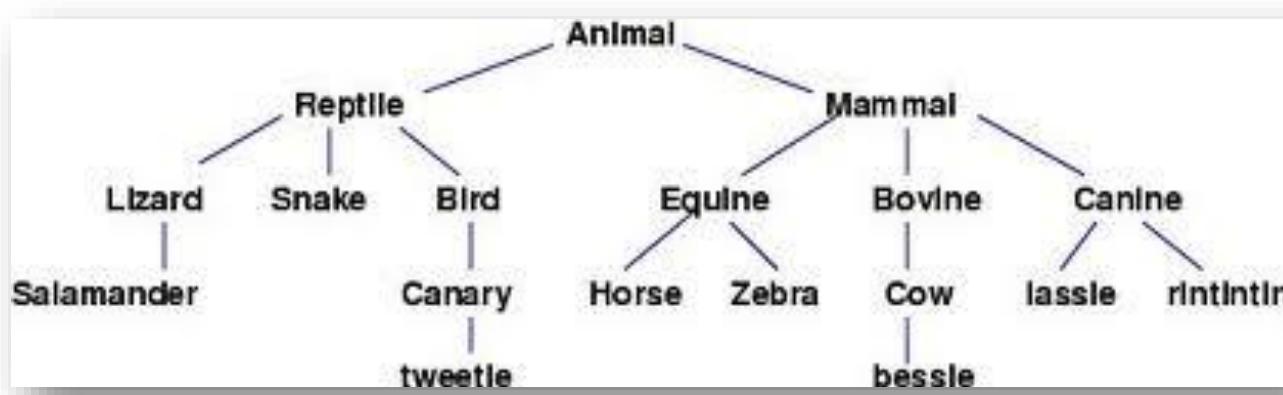
if $A \neq D$

D = Proper Decendent of A

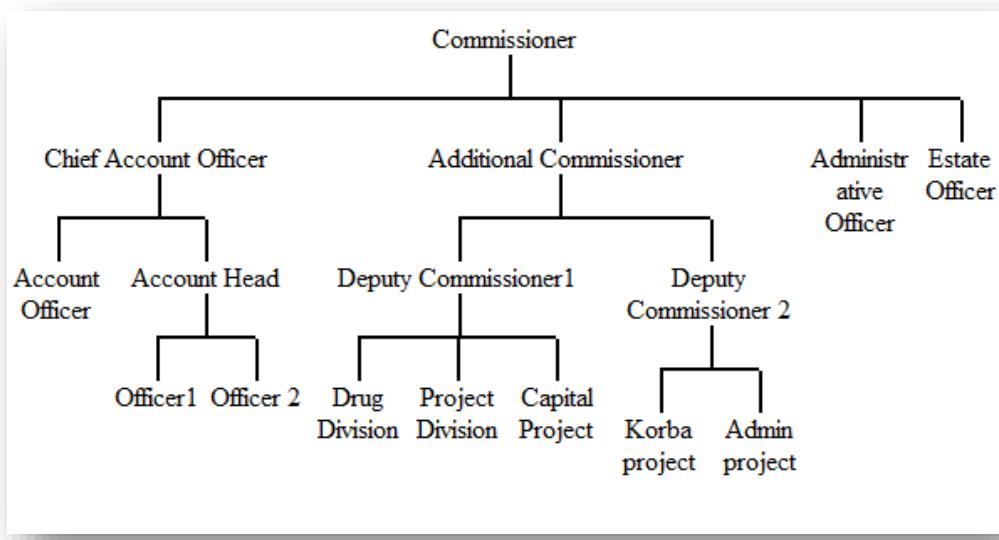
if $D \neq A$



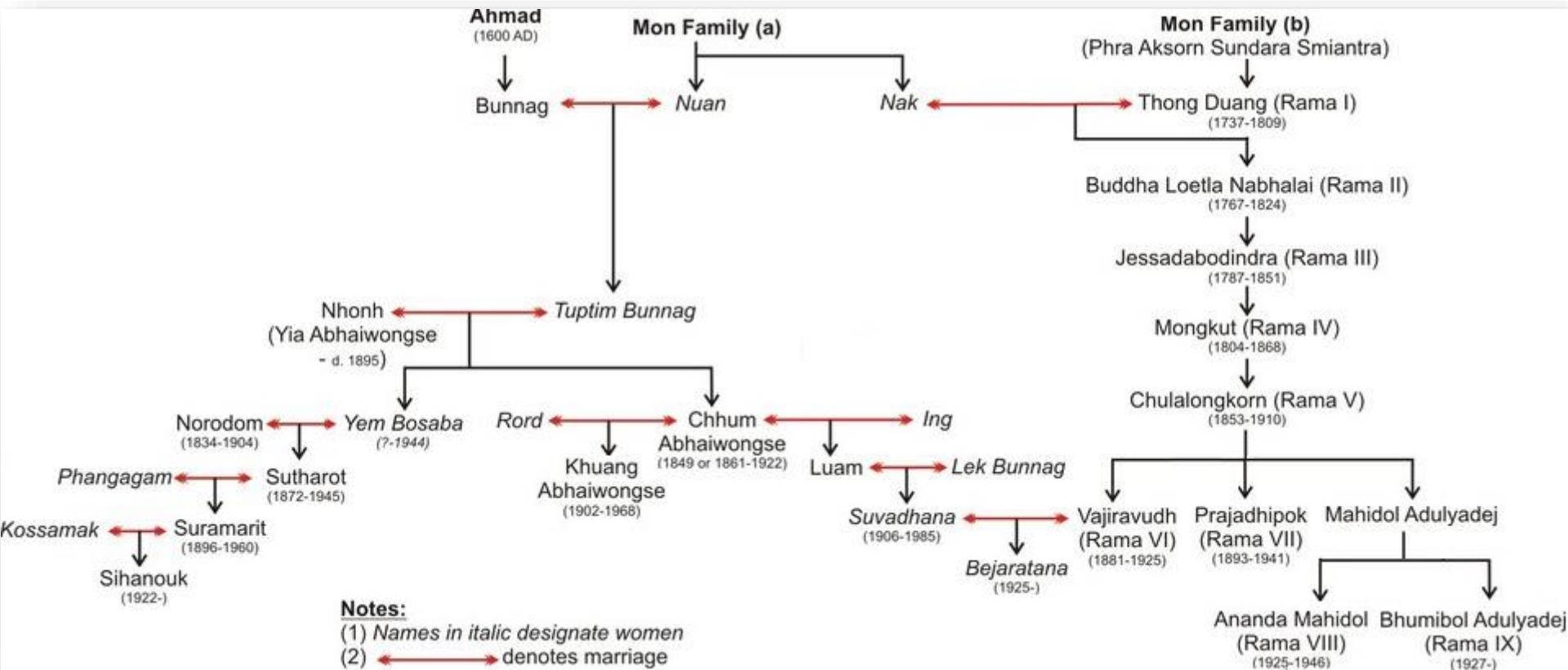
Tree Examples



Tree Examples



Thai Royal Family Tree

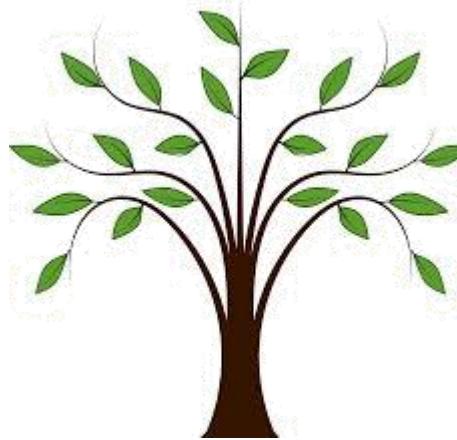


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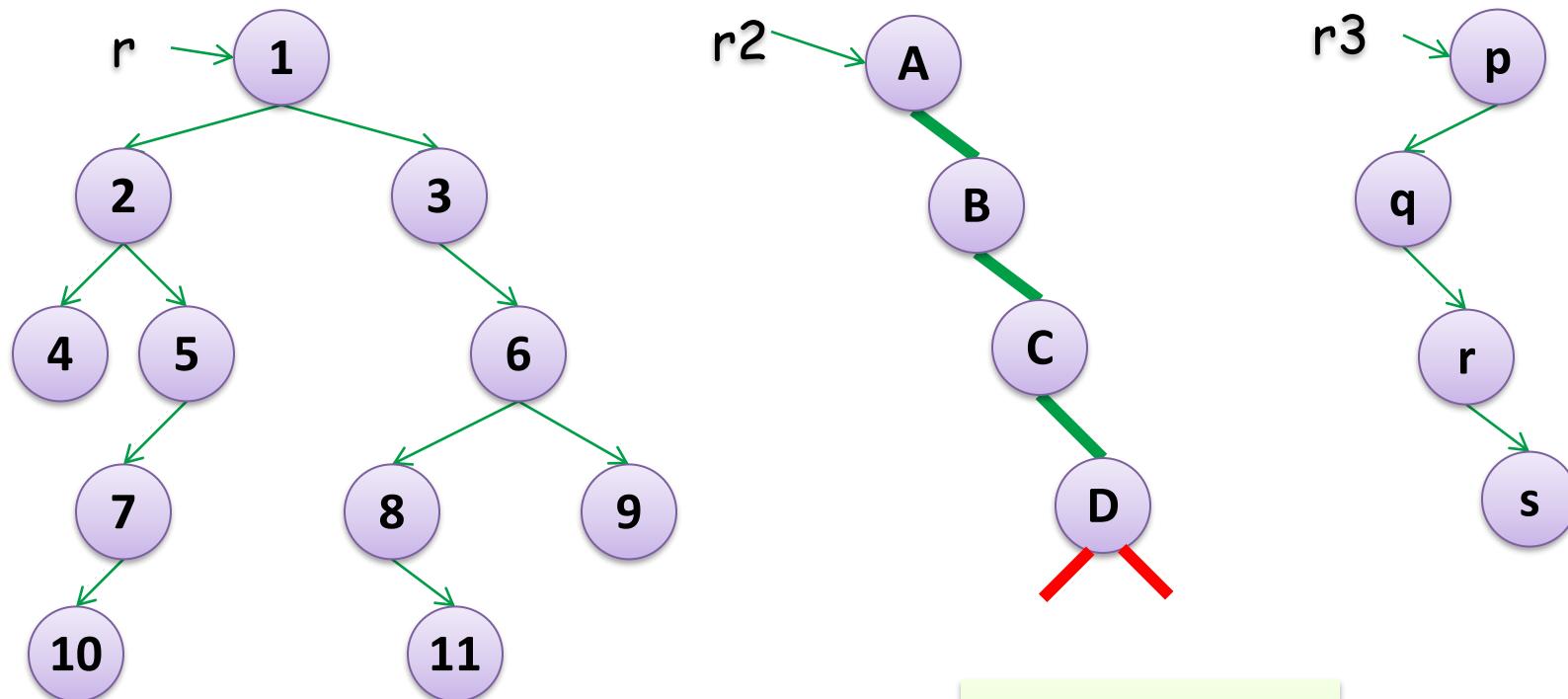


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Binary Tree

bi = 2

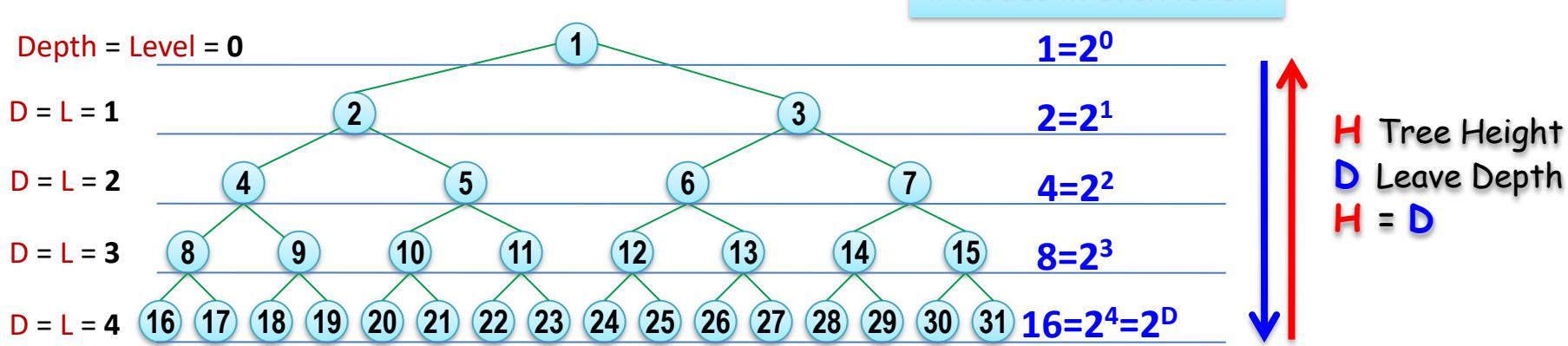
Binary Tree : มีอย่างมากที่สุด 2 subtrees (0, 1 or 2 subtrees)



Normally not draw
• branch direction
• null ptr

Perfect Binary Tree

Perfect Binary Tree (Ambiguously also called Complete Binary Tree) Every level is completely filled



N = จำนวน node ใน perfect binary tree

$$N = 2^0 + 2^1 + \dots + 2^H \quad \sum_{i=0}^N r^i = \frac{1 - r^{n+1}}{1 - r}, r <> 1$$

$$N = 2^{H+1} - 1$$

$$H = D = \log_2(N+1) - 1$$

$$O(\log_2(N))$$

$$N = (2^H \text{ external}) + (2^{H-1} \text{ internal})$$

Perfect Binary Tree of N nodes height H :

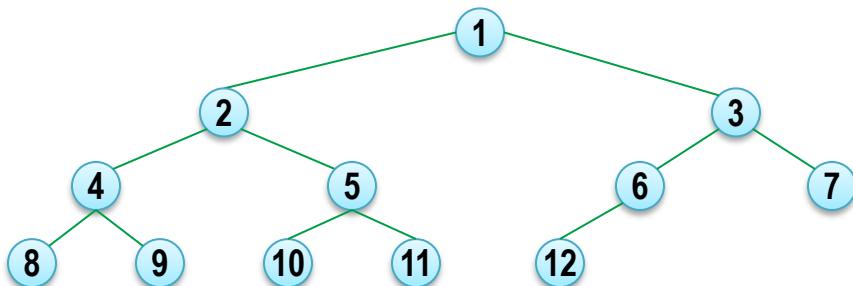
$$H = \log_2(N+1) - 1$$

$$N = 2^{H+1} - 1$$

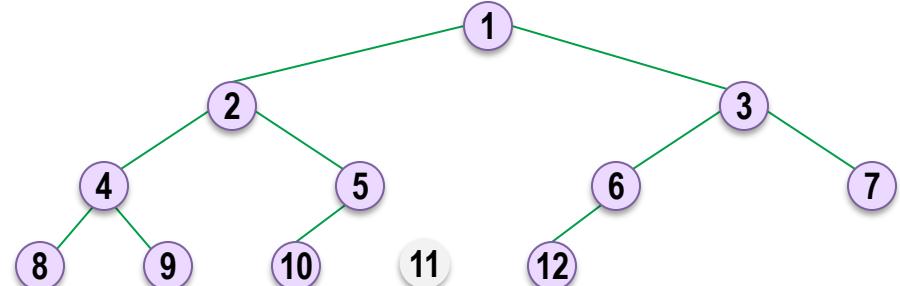
Complete Binary Tree

Complete Binary Tree

Every level, except possibly the last, is completely filled &
All nodes are as far left as possible.



Complete binary tree



Without node 11 :
Not a complete binary tree

Perfect Binary Tree & Complete Binary Tree

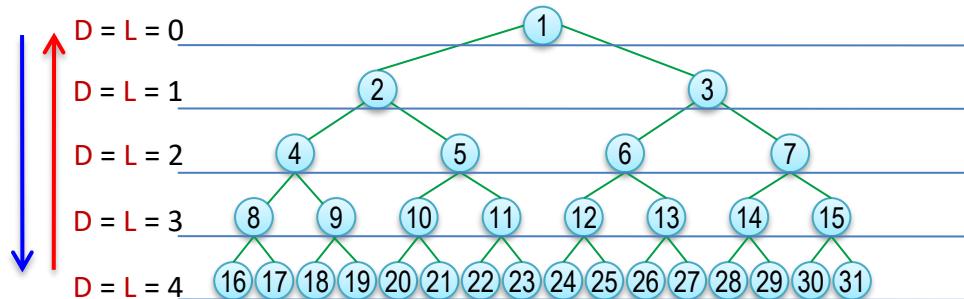
N จำนวน node และ H ความสูง

Perfect Binary Tree

$$\begin{aligned}
 H &= \log_2(N+1) - 1 \\
 &= \lfloor \log_2 N \rfloor \\
 N &= 2^{H+1} - 1
 \end{aligned}
 \rightarrow O(\log_2(N))$$

Complete Binary Tree

$$\begin{aligned}
 H &= \log_2(N+1) - 1 \\
 &= \lfloor \log_2 N \rfloor \\
 N &\text{ ระหว่าง } [2^H, 2^{H+1} - 1]
 \end{aligned}
 \rightarrow O(\log_2(N))$$



H Tree Height
D Leave Depth
H = D

Perfect Binary Tree
Every level is completely filled
(Ambiguously also called Complete Binary Tree)

$$\sum_{i=0}^N r^i = \frac{1-r^{n+1}}{1-r}, r \neq 1$$

Nodes
in each level

$1=2^0$

$2=2^1$

$4=2^2$

$8=2^3$

$16=2^4=2^D$

N total # of nodes

$= 2^0 + 2^1 + \dots + 2^H$

$= 2^{H+1} - 1$

เป็น external 2^H

internal $2^H - 1$

$2^H = 2^3 = 8$

$16 = 2^{H+1} = 2^4 = 16$

$\begin{aligned}
 2^{H+1} - 1 &= 2^4 \\
 &= 16 \\
 &= 15
 \end{aligned}$

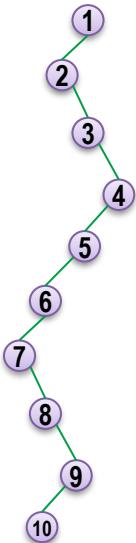
Complete Binary Tree

Every level is completely filled,
except possibly the last, &
All nodes are as far left as possible

Complete Binary Tree : H and N

How can 10 nodes in a binary tree has

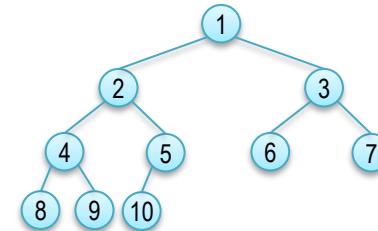
- longest search path ?
- shortest search path ?



Worst Case Height

Like Linked list : $H = N - 1$

$O(N)$



Best Case Height

Complete Binary Tree of N nodes height H :

$$H = D = \lceil \log_2 (N+1) - 1 \rceil = \lfloor \log_2 N \rfloor$$

$O(\log N)$

How much different N vs $\log_2 N$?

$\log_2 1,000,000 < 20$

So
Complete Binary Tree
is an **ideal tree**

Full (proper, strictly, 2-tree) Binary Tree

Full Node = node with 2 children

Full binary tree

node = full node or leaf

external = # internal + 1

Proof :

$$\text{edge top} = 2 \# \text{internal}$$

$$\text{edge bottom} = \# \text{external} + \# \text{internal} - 1 \text{ (root)}$$

$$\text{edge bottom} = \text{edge top}$$

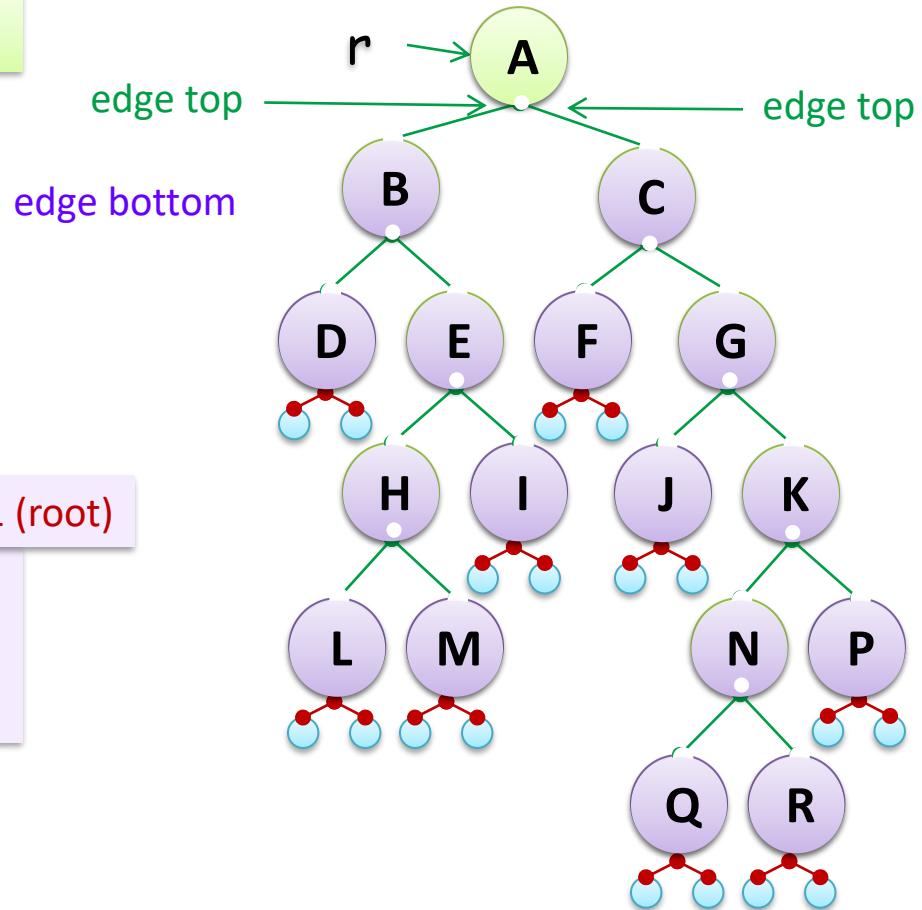
$$\therefore \# \text{external} + \# \text{internal} - 1 = 2 \# \text{internal}$$

$$\# \text{external} = \# \text{internal} + 1$$

How good ?

Try add every leaf with 2 sons.

See how good?



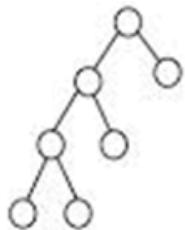
Before : N = 17

Max Search Path = Tree's Height

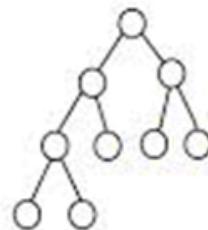
Add = 18 more

Max Search Path
increases only 1

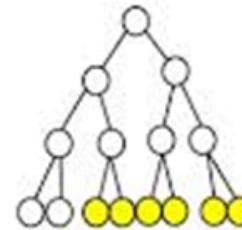
Full Complete Perfect



full

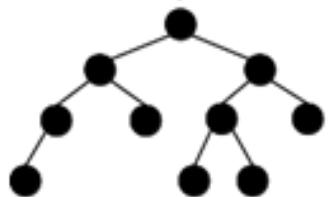


complete

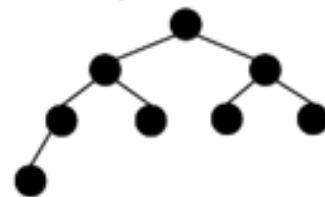


perfect

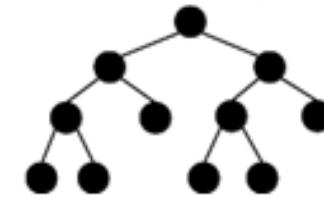
Neither complete nor full



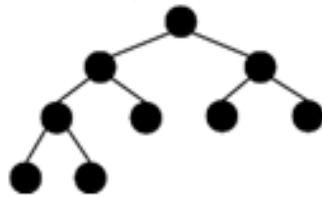
Complete but not full



Full but not complete



Complete and full

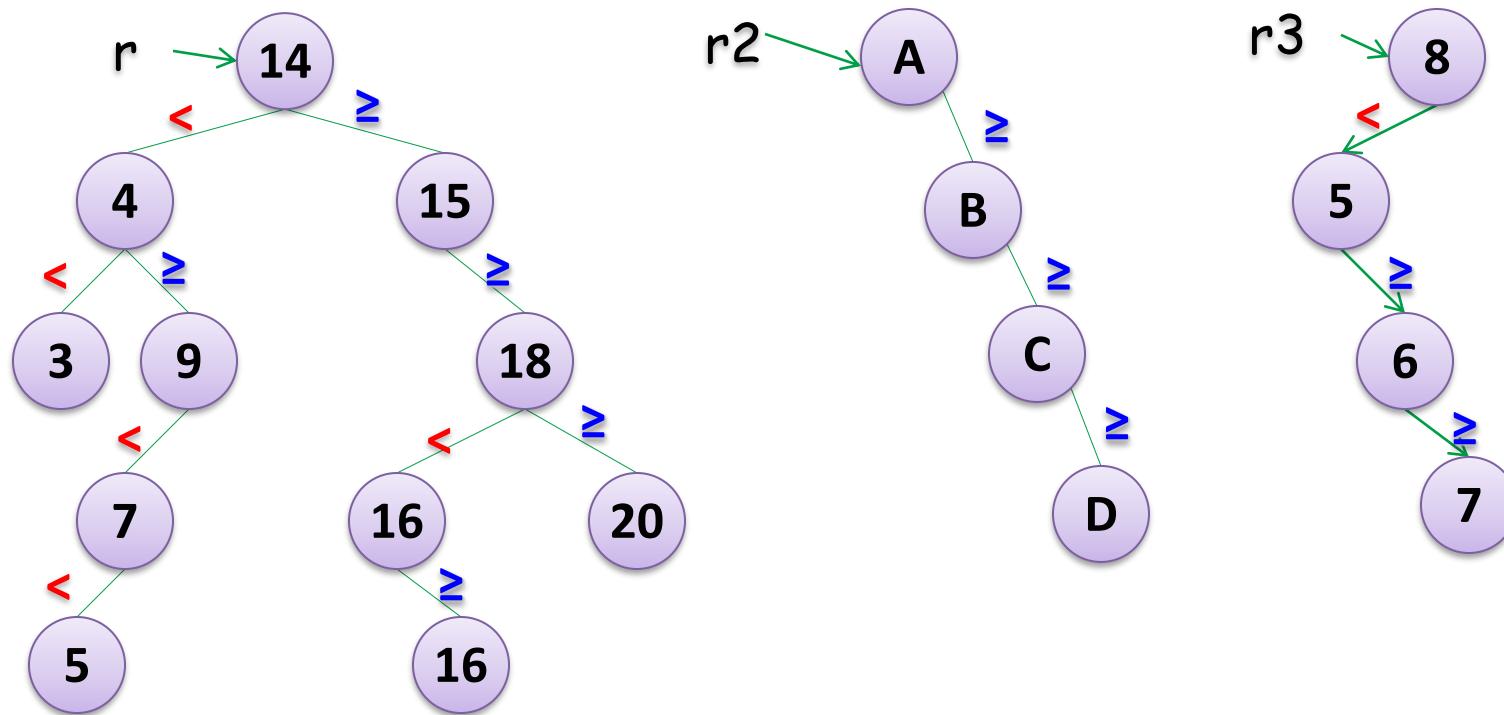


Binary Search Tree

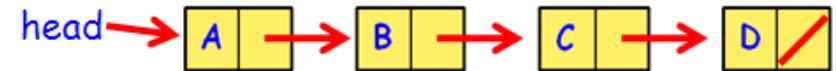
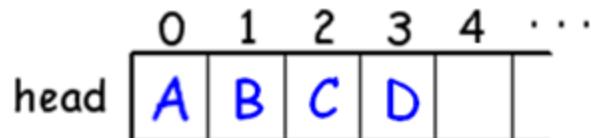
Binary Search Tree : for every node A

left decendents $< A$

right decendents $\geq A$



Why Tree ?



Implicit (Sequential) Array
Insertion – Deletion Problems

Linear Linked list
Linear Search

$O(n)$



Tree
Tree Search

$O(\log_2 n)$

UNIX

File system of several popular OS

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Tree Traversal

การไปเยี่ยม (visit เช่นการพิมพ์ การ update ข้อมูล) ทุก node node จะ 1 ครั้ง อย่างมีระบบ
แบ่งตามลำดับของการ visit

Breadth First (Level Order) จาก root ไปด้านข้างก่อน

- ลูกคนแรก ลูกคนที่ 2 ลูกคนที่ 3 ... จนหมดลูกทุกคน
- ทำข้อ 1. กับทุกคนที่ไปเยี่ยมมาตามลำดับ

Depth-First Order จาก root ไปด้านลึกก่อน ไปด้านข้าง

ลูกคนแรก และไปหานคนแรกก่อน ไปที่ลูกคนที่ 2

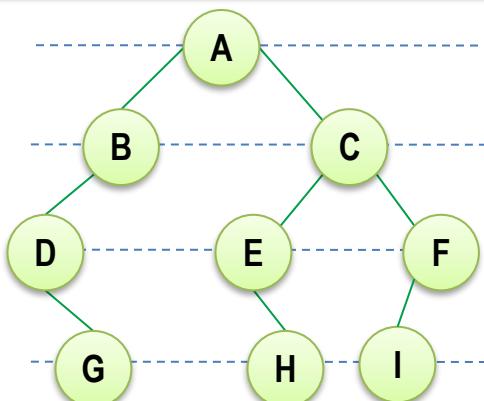
Breadth - First (Level Order)

Breadth First จาก root ไปด้านข้างก่อน ใช้ queue ช่วยในการหา

- ลูกคนแรก ลูกคนที่ 2 ลูกคนที่ 3 ...จนหมดลูกทุกคน
- ทำข้อ 1. กับทุกคนที่ไปเยี่ยมมาตามลำดับ

A B C D E F G H I

ໄລ'ไปทีละ level จึงเรียกอีกอย่างหนึ่งว่า Level Order



queue



deQ & visit

```
enQ ( root )
while ( notEmptyQ ) {
    n = deQ ( )
    visit(n)
    if ( n->left )
        enQ ( n->left )
    if ( n->right )
        enQ ( n-> right )
}
```

Depth - First Order

Depth-First Order จาก root ไปด้านลึกก่อน ไปด้านข้าง ใช้ stack ช่วยในการหาไปลูกคนแรก และไปหานคนแรกก่อนไปที่ลูกคนที่ 2
แบ่งเป็น 3 แบบ ขึ้นกับการวางแผนการ visit root ไว้ที่ใด

Inorder (Symmetric Order)

1. inOrder(leftSubtree)
2. **visit_root**
3. inOrder(rightSubtree)

Preorder

1. **visit_root**
2. preOrder(leftSubtree)
3. preOrder(rightSubtree)

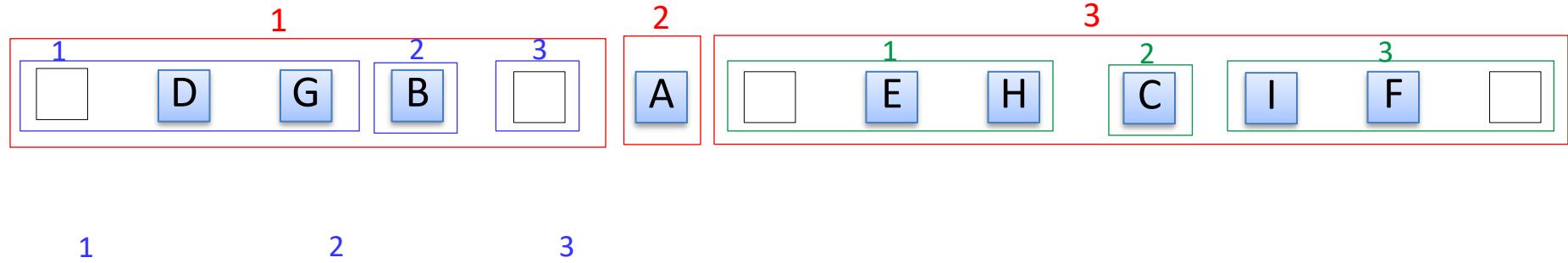
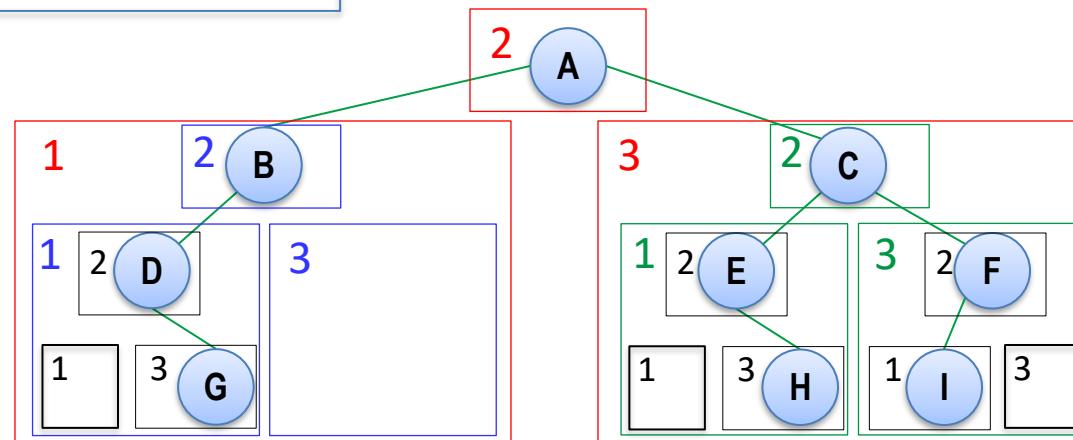
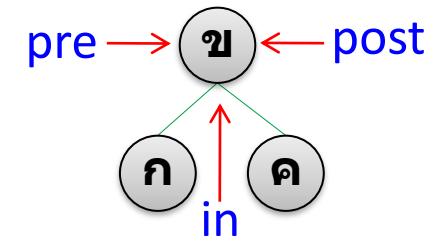
Postorder

1. postOrder(leftSubtree)
2. postOrder(rightSubtree)
3. **visit_root**

Inorder (Symmetric Order)

Algorithm:

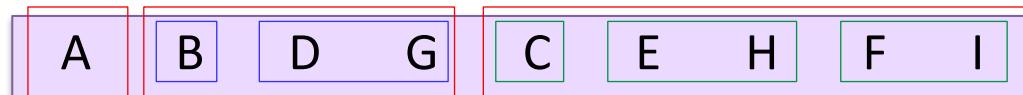
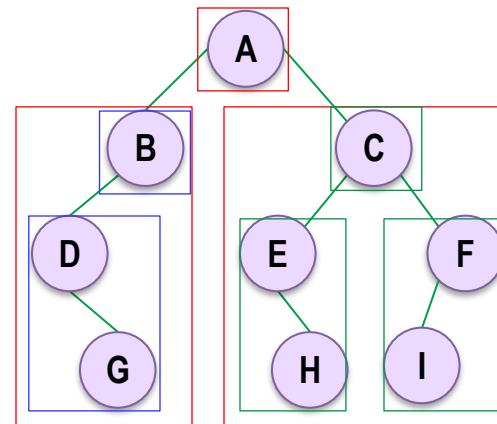
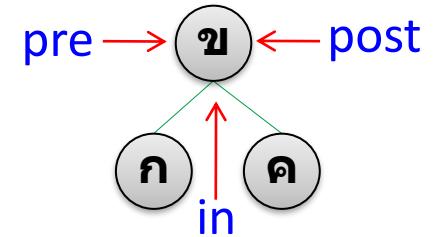
```
inOrder( root ) {  
    if (root != null){  
        inOrder(left subtree)  
        visit(root)  
        inOrder(right subtree)  
    }  
}
```



Preorder

Algorithm:

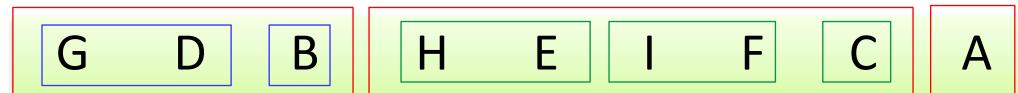
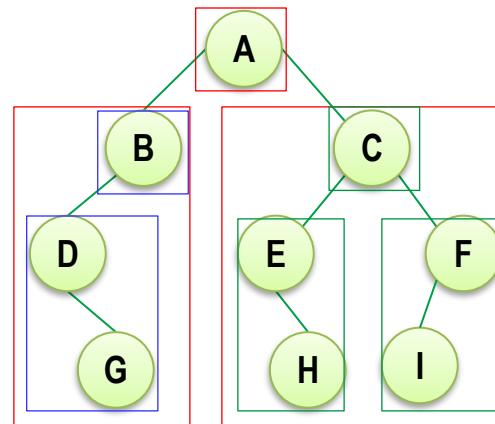
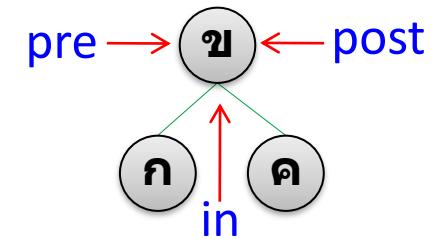
```
preOrder( root ) {  
    if (root != null){  
        visit(root)  
        preOrder(left subtree)  
        preOrder(right subtree)  
    }  
}
```



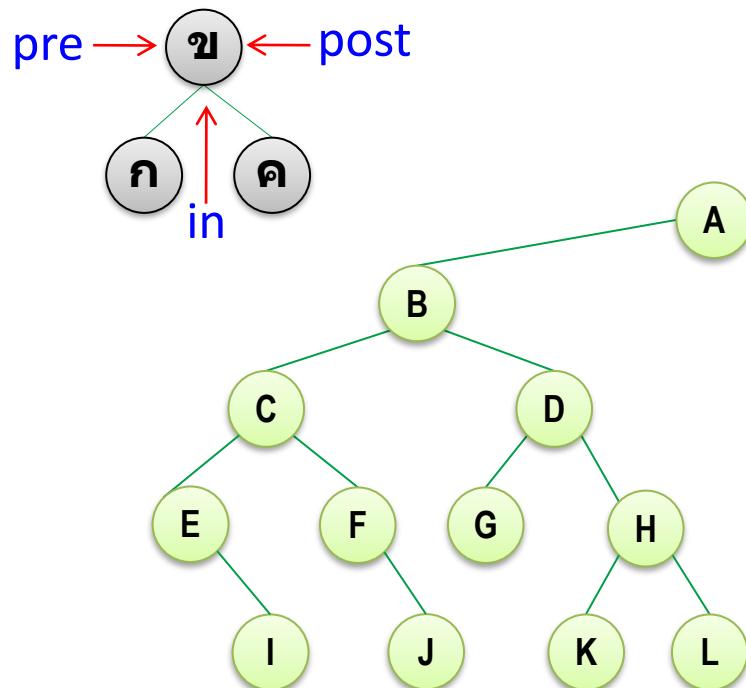
Postorder

Algorithm:

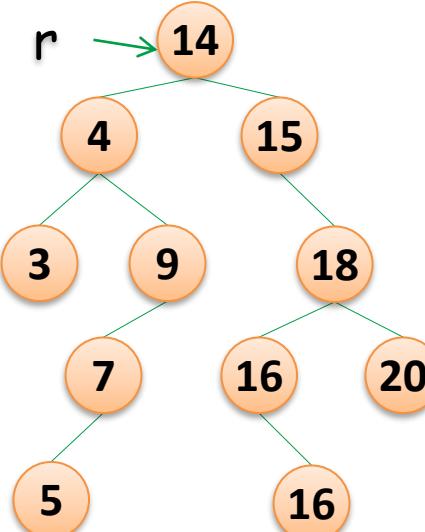
```
postOrder( root ) {  
    if (root != null){  
        postOrder(left subtree)  
        postOrder(right subtree)  
        visit(root)  
    }  
}
```



Test Your Self



Binary Search Tree



Inorder : LrootR

1. inOrder(L)
2. visit_root
3. inOrder(R)

Postorder : LRroot

Preorder : rootLR

Inorder

E I C F J B G D K H L A

3 4 5 7 9 14 15 16 16 18 20

Ascending Order !

Preorder

A B C E I F J D G H K L

14 4 3 9 7 5 15 18 16 16 20

Postorder

I E J F C G K L H D B A

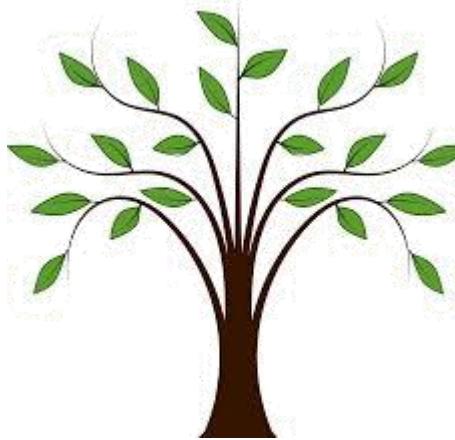
3 5 7 9 4 16 16 20 18 15 14

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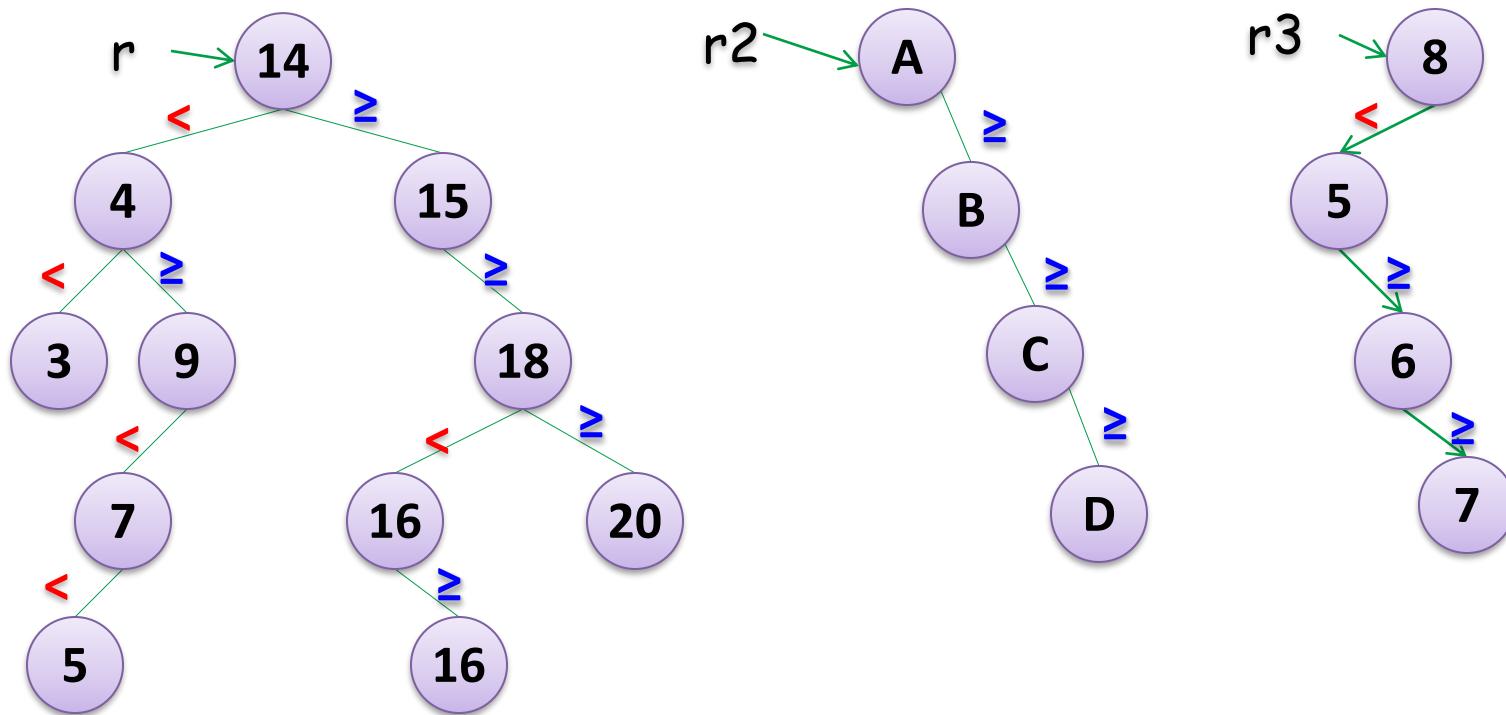
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Binary SearchTree

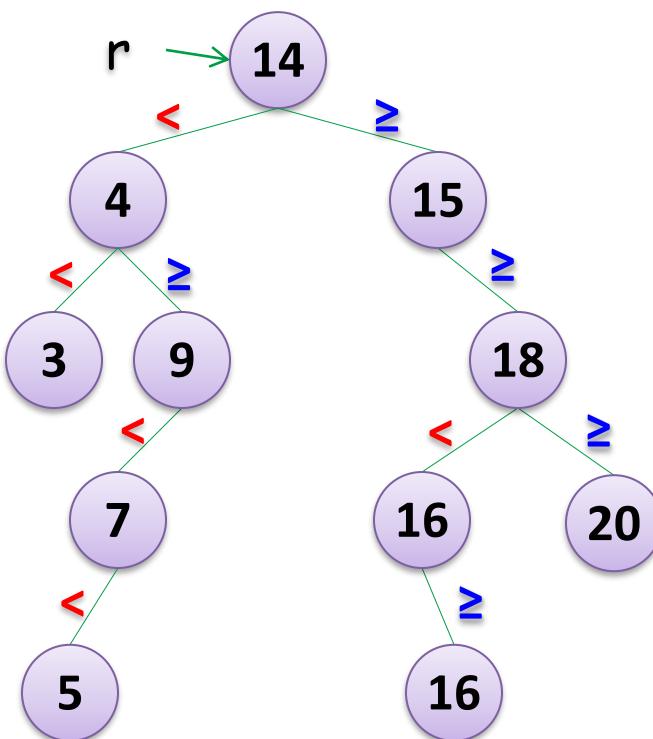
Binary Search Tree : for every node A

left decendents $< A$

right decendents $\geq A$

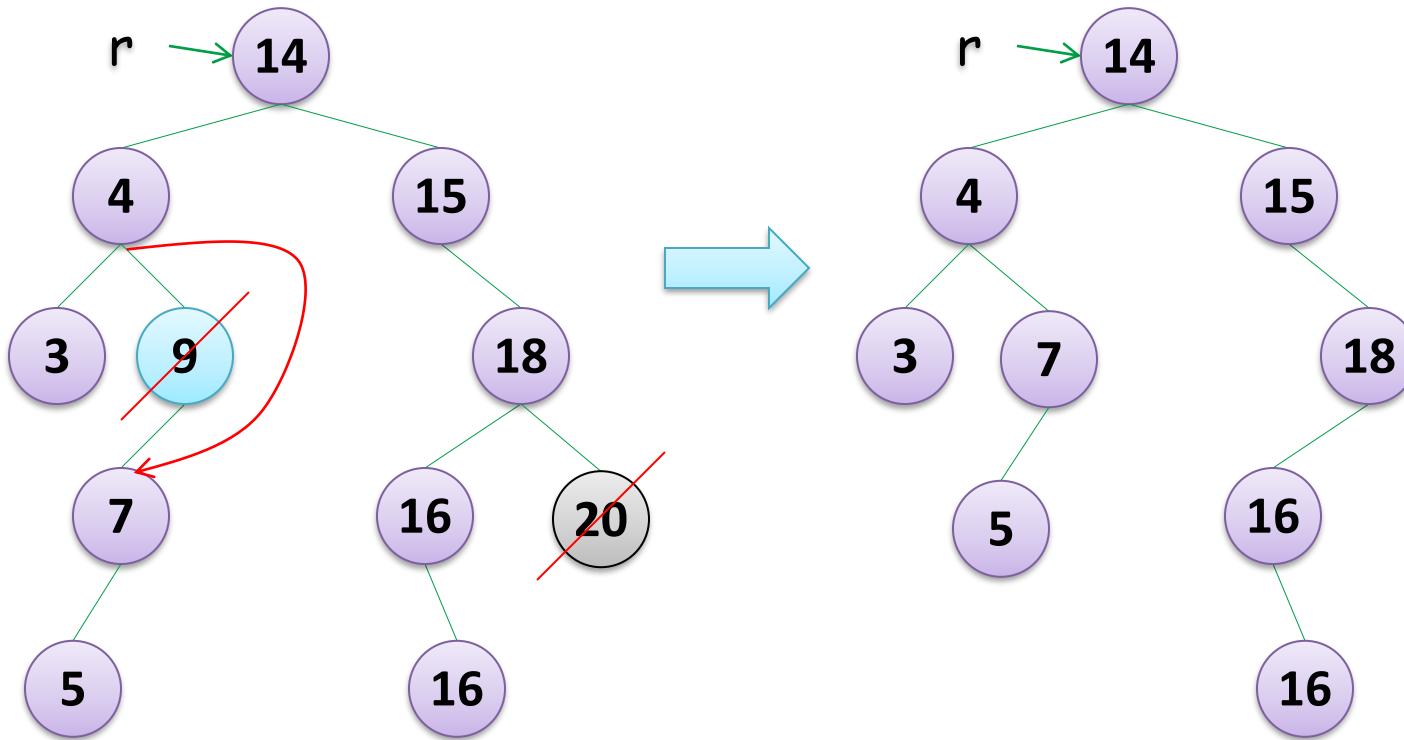


Insertion



Inserts : 14 4 9 7 15 3 18 16 20 5 16

Delete a : Leaf, Node with only 1 child



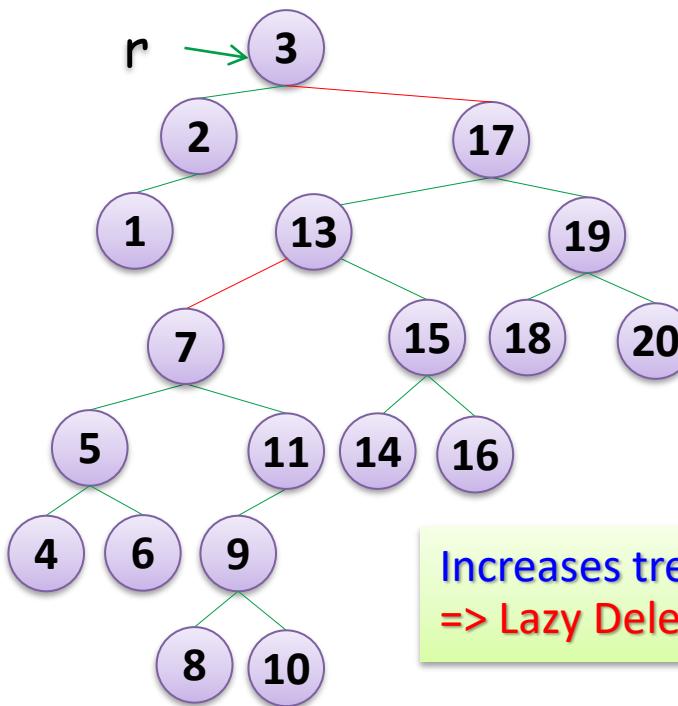
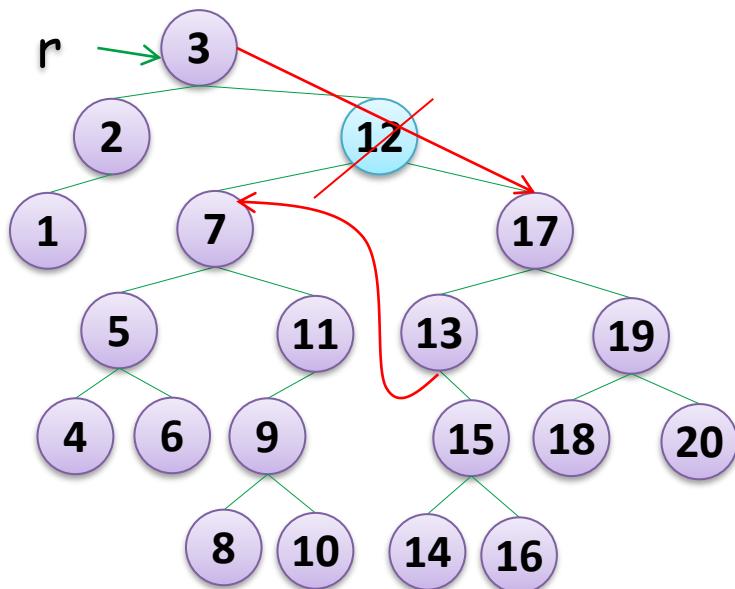
Delete Leaf

20 can be deleted right away, still be a binary search tree

Delete a node with only one child

Delete 9, replace a subtree at the deleted node

Delete a Node with Both Children : Lazy Deletion 1



Delete 12

Where can we put tree 7, and tree 17 ?

Can replace only 1 at the deleted node.

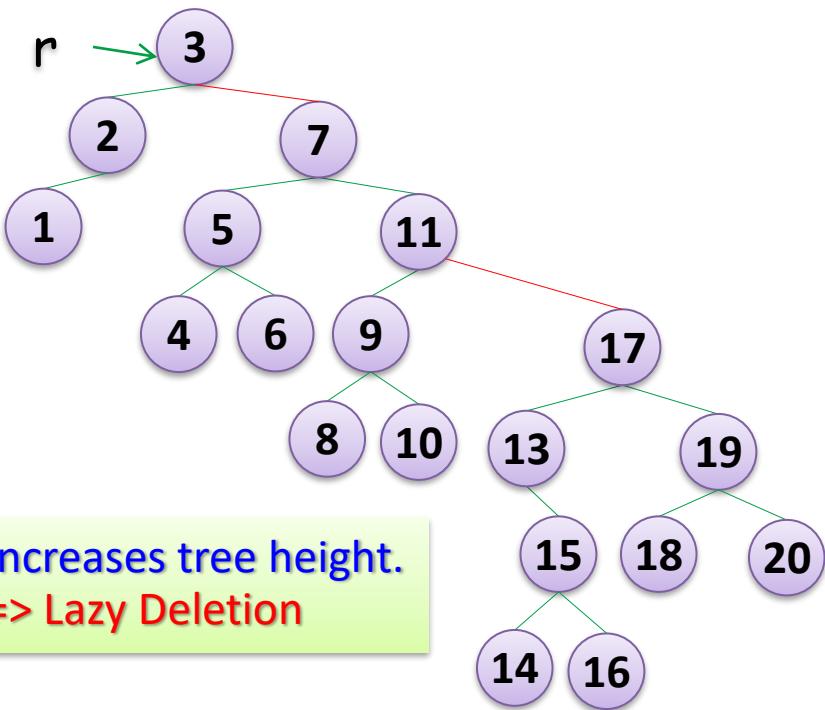
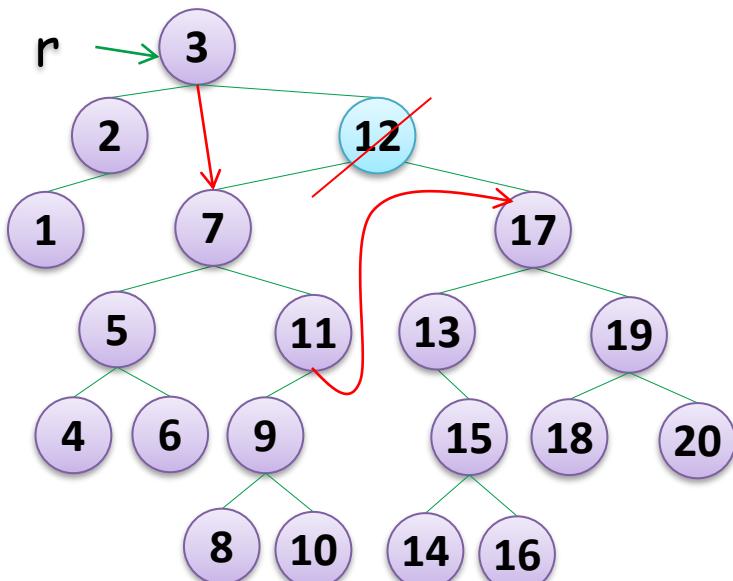
Let choose 17.

Where to put tree 7 ?

It's a binary search tree!

Where is its place ?

Delete a Node with Both Children : Lazy Deletion 2

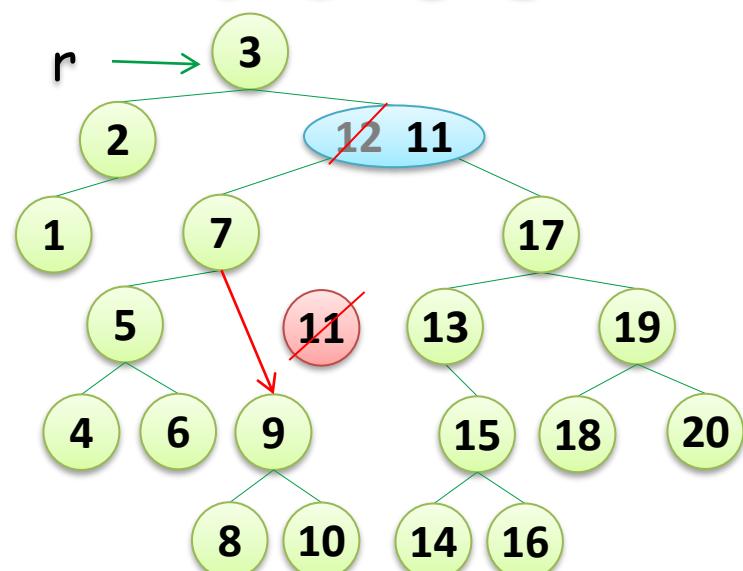
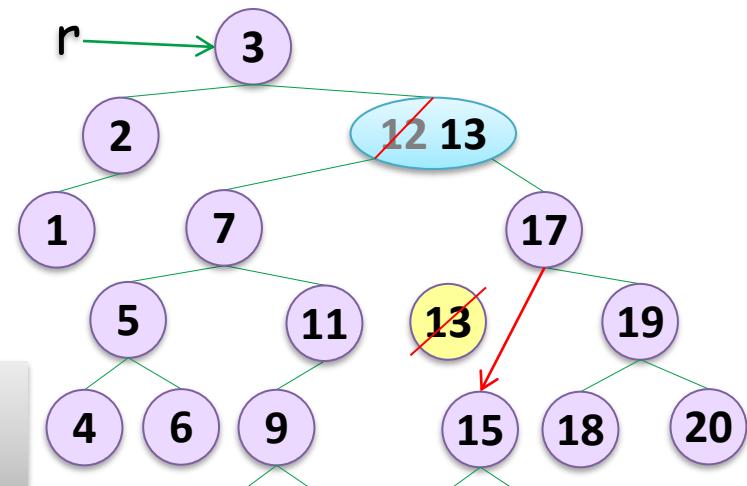
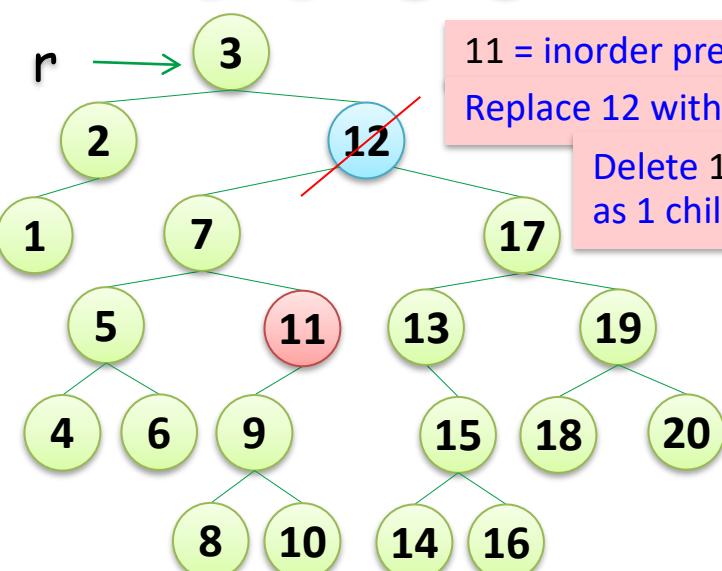
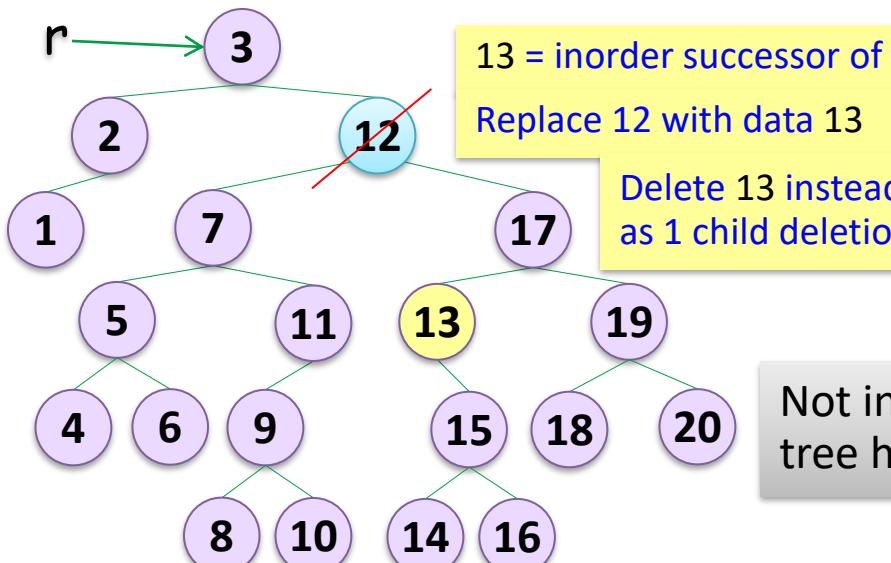


Delete 12

Can replace only 1 at the deleted node.

If we choose 7. Where is 17's place ?

Deletion : Using Inorder Successor / Predecessor

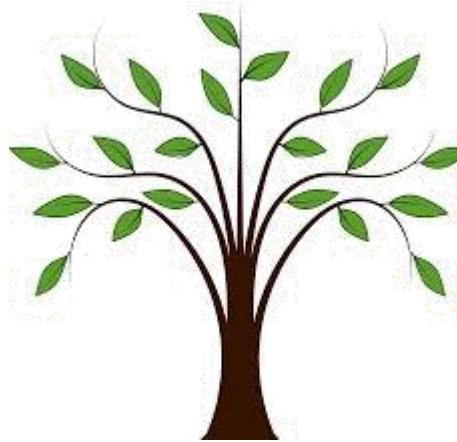


Tree

1. Tree Definitions

2. Binary Tree

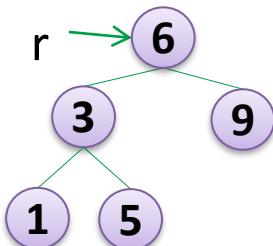
- Traversals
- Binary Search Tree
- **Representations**
- Application : Expression Tree



- 3. AVL Tree
- 4. Which Representations ?
- 5. n-ary Tree
- 6. Generic Tree
- 7. Multiway Search Tree
- 8. B-Trees

Binary Tree Representations

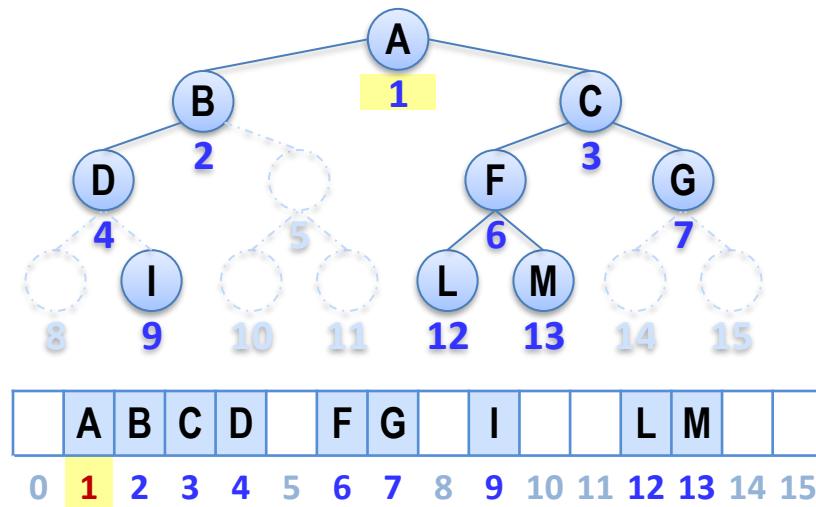
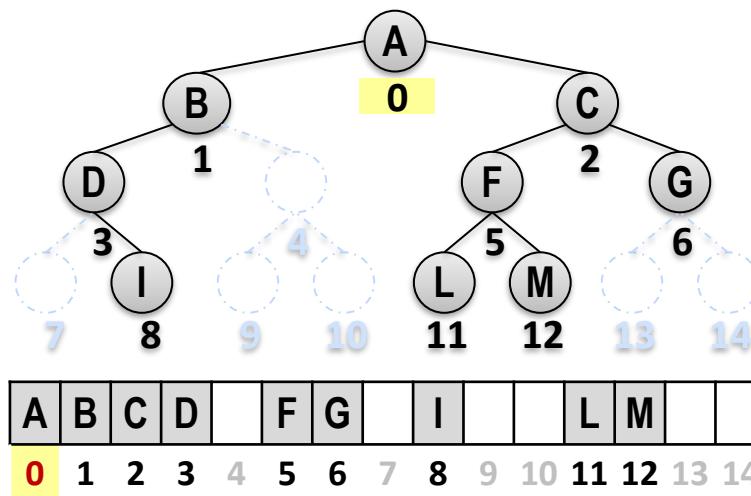
1. Dynamic



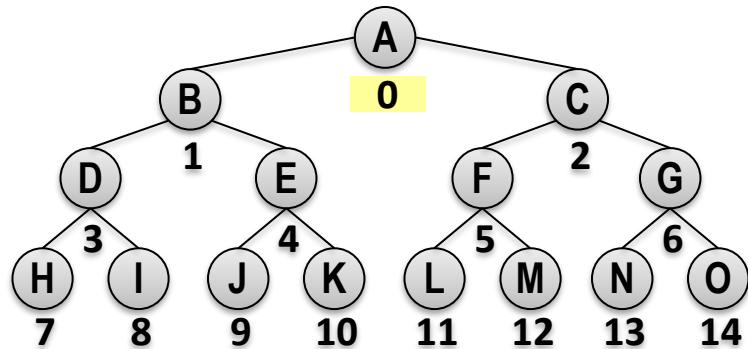
class node:

```
def __init__(self, data, left = None, right = None):  
    self.data = data  
    self.left = None if left is None else left  
    self.right = None if right is None else right
```

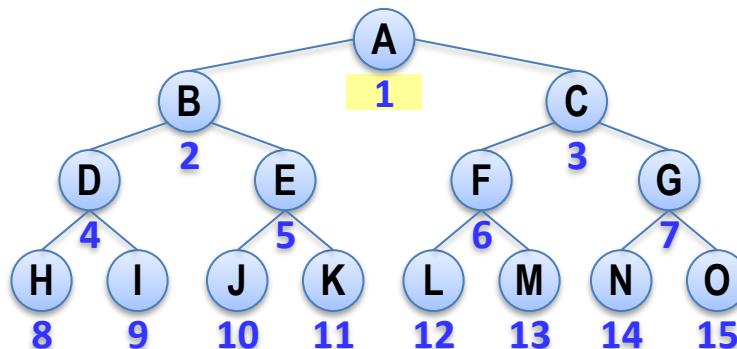
2. Sequential (Implicit) Array



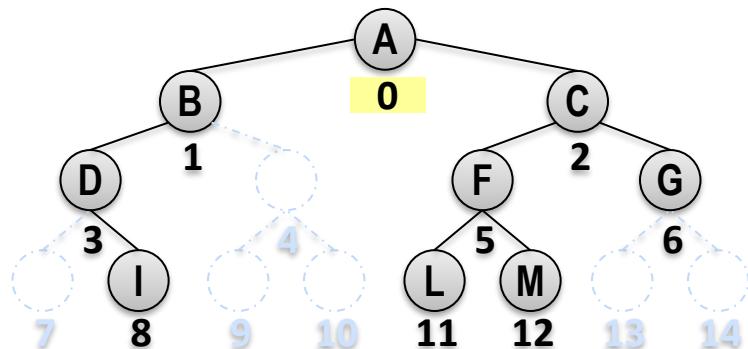
(Sequential) Implicit Array



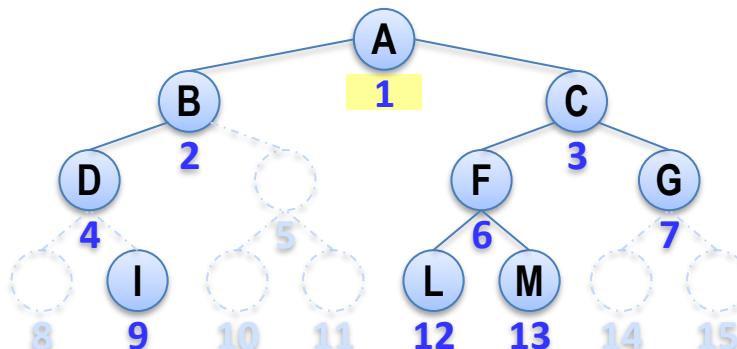
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

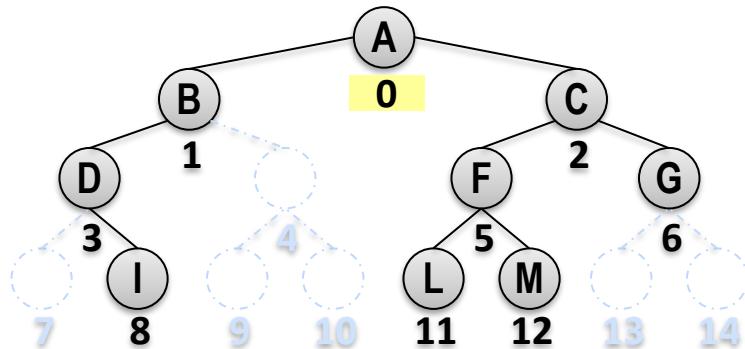


A	B	C	D		F	G		I		L	M			
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

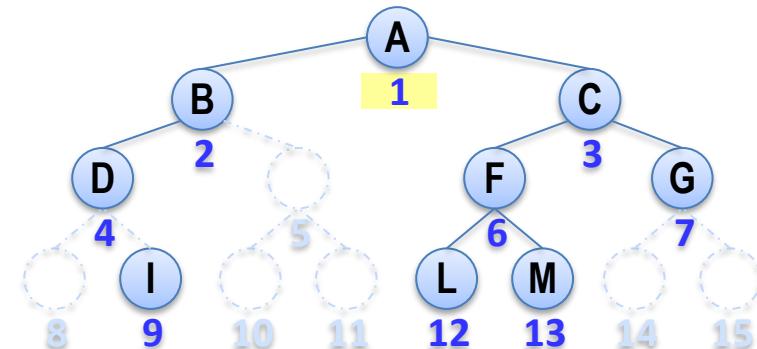


	A	B	C	D		F	G		I		L	M		
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

(Sequential) Implicit Array



A	B	C	D	F	G	I		L	M		
0	1	2	3	4	5	6	7	8	9	10	11



	A	B	C	D	F	G	I		L	M	
0	1	2	3	4	5	6	7	8	9	10	11

Where is the **root** ?

The node at index i 's **left son** ?

right son ?

father ?

Start at index 0

0

$2i + 1$

$2i + 2$

$(i - 1) \text{ div } 2$

Start at index 1

1

$2i$

$2i + 1$

$i \text{ div } 2$

So good ! No memory for link ! Easy to calculate !

What happen if we have **only** node at indices : 0, 2, 6, 14 ? ie. **sparse**

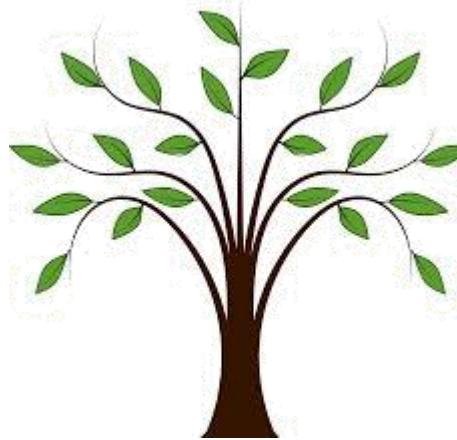
What shape of tree should be best for sequential array?

Tree

1. Tree Definitions

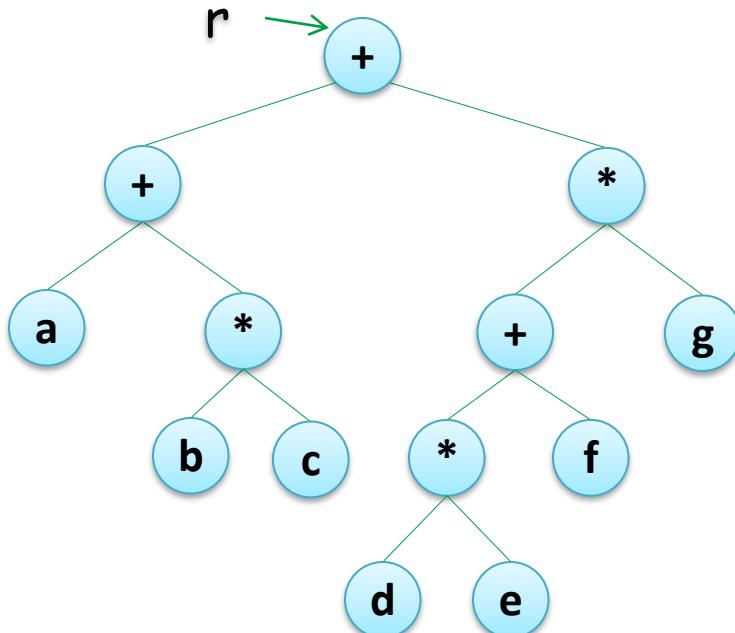
2. Binary Tree

- Traversals
- Binary Search Tree
- Representations
- Application : Expression Tree

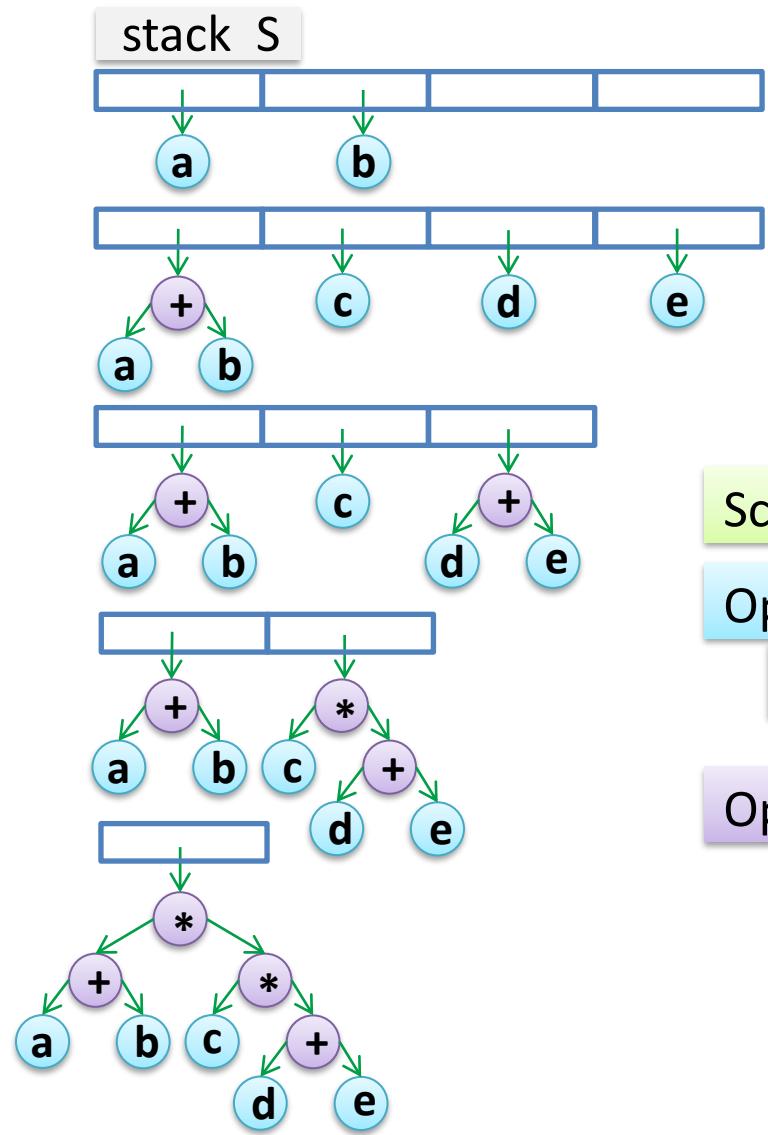


- 3. AVL Tree
- 4. Which Representations ?
- 5. n-ary Tree
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Example : Expression Tree


$$(a + b * c) + ((d * e + f) * g)$$

Constructing an Expression Tree



input postfix form

a b + c d e + * *

Scan input from left to right.

Operand

Create an operand node and push to the stack

Operator

Create an operator node

Pop 2 operands to be its children.

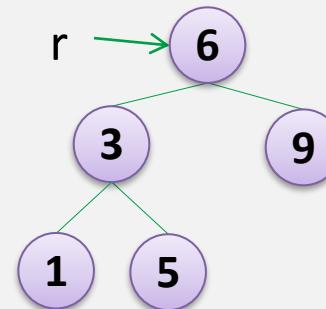
Push to the stack.

Node

```
class node:  
    def __init__(self, data, left = None, right = None):  
        self.data = data  
        self.left = None if left is None else left  
        self.right = None if right is None else right  
  
    def __str__(self):  
        return str(self.data)  
  
    def getData(self):          # accessor  
        return self.data  
  
    def getLeft(self):          # accessor  
        return self.left  
  
    def getRight(self):         # accessor  
        return self.right  
  
    def setData(self, data):    # mutator  
        self.data = data  
  
    def setLeft(self, left):    # mutator  
        self.left = left  
  
    def setRight(self, right):  # mutator  
        self.right = right
```

Dynamic Representation 1

```
class BST:  
    def __init__(self, root = None):  
        self.root = None if root is None else root  
  
    def addI(self, data):  
        if self.root is None:  
            self.root = node(data)  
        else:  
            # YOUR CODE  
  
    def add(self, data):  
        self.root = BST._add(self.root, data)  
  
    def _add(root, data):  
        if root is None:  
            return node(data)  
        else:  
            if data < root.data:  
                root.left = BST._add(root.left, data)  
            else:  
                root.right = BST._add(root.right, data)  
        return root
```



```
if data < root.getData():  
    root.setLeft(BST._add(root.getLeft(), data))  
else:  
    root.setRight(BST._add(root.getRight(), data))
```