

CS101 Data Structures

Binary Trees

Textbook Ch B.5.3, 10.4

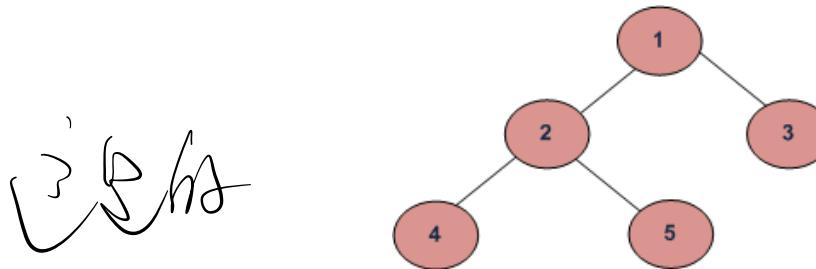
Orders of DFS traversal



- Inorder (Left, Root, Right) : 4 2 5 1 3
- Preorder (Root, Left, Right) : 1 2 4 5 3
- Postorder (Left, Right, Root) : 4 5 2 3 1
- Breadth-First or Level Order Traversal: 1 2 3 4 5



先父后子
先子后父



先父后子
先子后父

Outline

- Binary tree
- Perfect binary tree
- Complete binary tree
- Left-child right-sibling binary tree

Outline

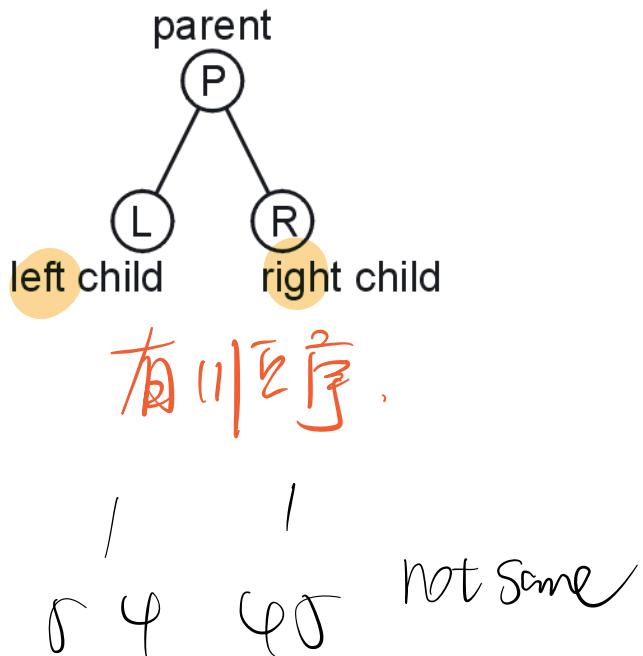
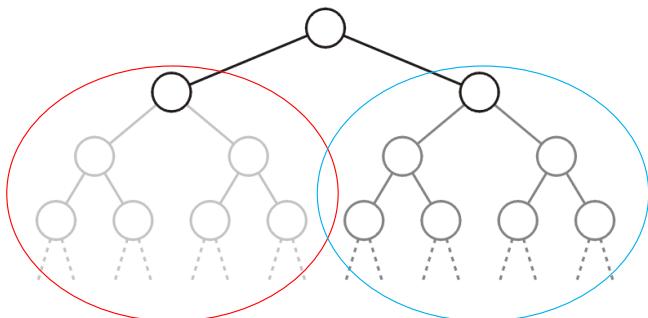
In this talk, we will look at the binary tree data structure:

- Definition
- Properties
- Application
 - Expression trees

Definition

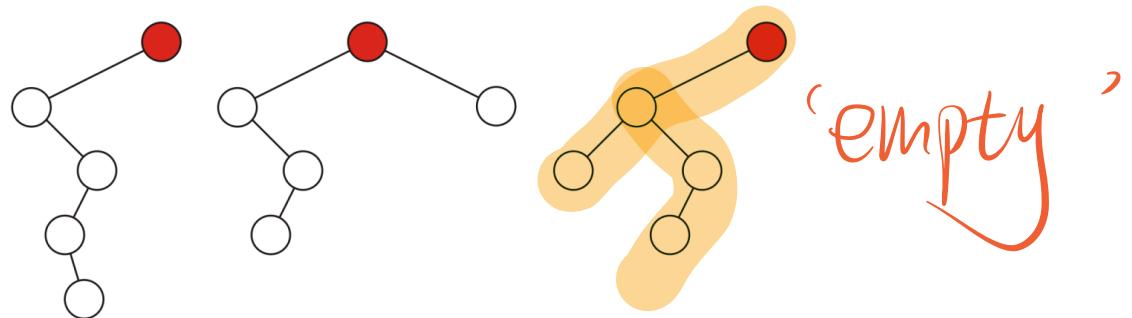
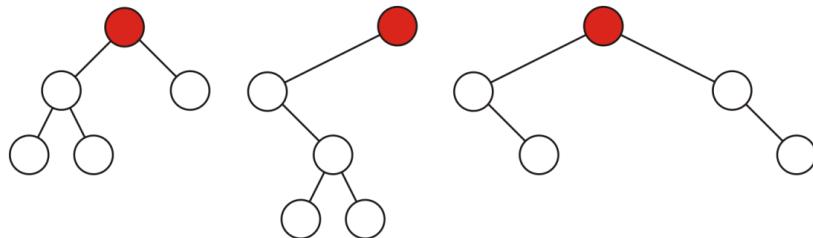
A binary tree is a restriction where each node has exactly two children:

- Each child is either **empty** or another binary tree
- This restriction allows us to label the children as *left* and *right* subtrees



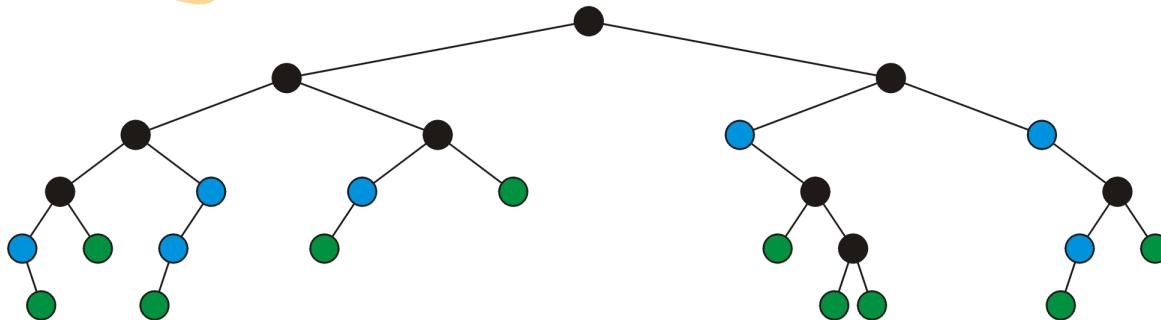
Definition

Some binary trees with five nodes:



Definition

A *full node* is a node where both the left and right sub-trees are non-empty trees



Legend:

full nodes



neither

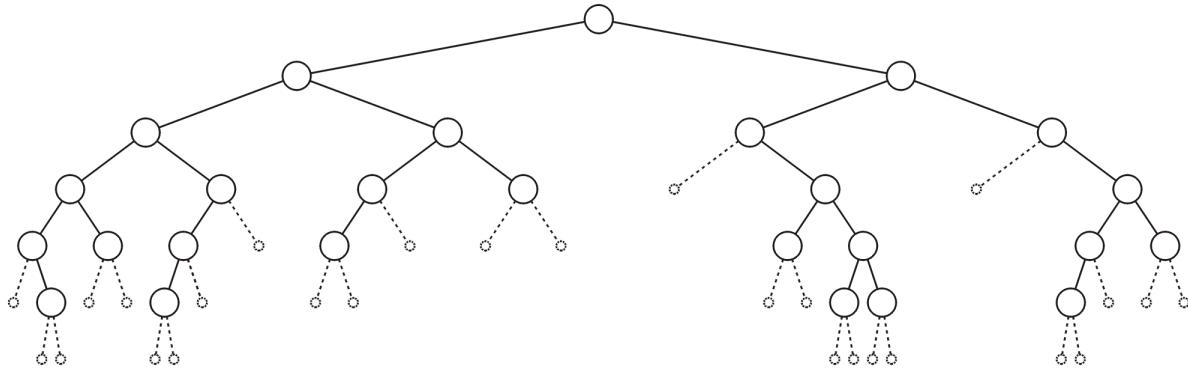


leaf nodes



Definition

An *empty node* or a *null sub-tree* is any location where a new leaf node could be appended



full

full or leaf

perfect

node full

complete

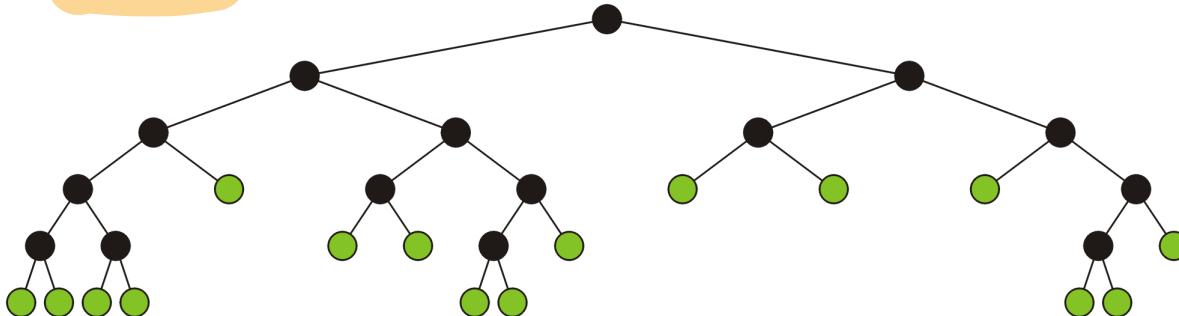
h - full

node

Definition

A *full binary tree* is where each node is:

- A full node, or
- A leaf node



These have applications in

- Expression trees
- Huffman encoding

imple

Binary Node Class



The binary node class is similar to the single node class:

```
template <typename Type>
class Binary_node {
protected:
    Type element;
    Binary_node *left_tree;
    Binary_node *right_tree;

public:
    Binary_node( Type const & );
    Type retrieve() const;
    Binary_node *left() const;
    Binary_node *right() const;
    bool is_leaf() const;
    int size() const;
}
```



Binary Node Class

We will usually only construct new leaf nodes

```
template <typename Type>
Binary_node<Type>::Binary_node( Type const &obj ):
    element( obj ),
    left_tree( nullptr ),
    right_tree( nullptr ) {
    // Empty constructor
}
```



Binary Node Class

The accessors are similar to that of `Single_list`

```
template <typename Type>
Type Binary_node<Type>::retrieve() const {
    return element;
}
```

```
template <typename Type>
Binary_node<Type> *Binary_node<Type>::left() const {
    return left_tree;
}
```

```
template <typename Type>
Binary_node<Type> *Binary_node<Type>::right() const {
    return right_tree;
}
```

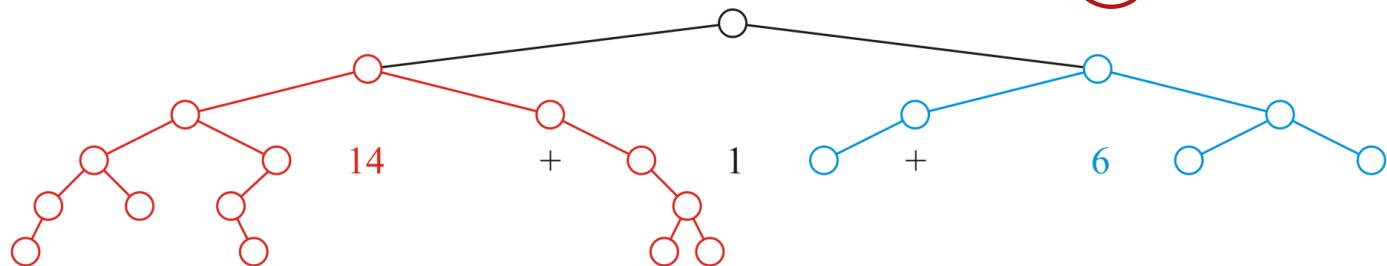


Binary Node Class

```
template <typename Type>
bool Binary_node<Type>::is_leaf() const {
    return left() == nullptr && right() == nullptr;
}
```

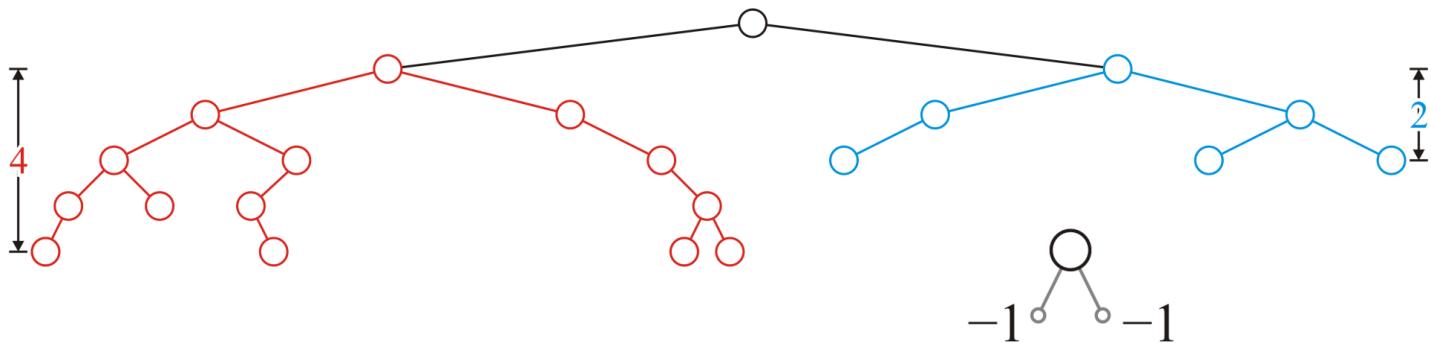
Size

```
template <typename Type>
int Binary_node<Type>::size() const {
    return 1
        + left() == nullptr? 0 : left()->size()
        + right() == nullptr? 0 : right()->size();
}
```



Height

```
template <typename Type>
int Binary_node<Type>::height() const {
    return empty() ? -1 :
        1 + std::max( left()->height(), right()->height() );
}
```



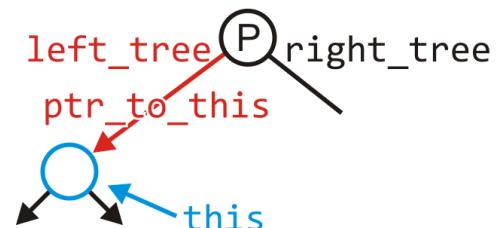
Clear

Removing all the nodes in a tree is similarly recursive:

```
template <typename Type>
void Binary_node<Type>::clear( Binary_node *&ptr_to_this ) {
    if ( empty() ) {
        return;
    }

    left()->clear( left_node );
    right()->clear( right_node );

    delete this;
ptr_to_this = nullptr;
}
```



Run Times

Recall that with linked lists and arrays, some operations would run in $\Theta(n)$ time

The run times of operations on binary trees, we will see, depends on the height of the tree

We will see that:

- The worst is clearly $\Theta(n)$
- Under average conditions, the height is $O(\sqrt{n})$
- The best case is $\Theta(\ln(n))$

CL

Run Times

If we can achieve and maintain a height $(\lg(n))$, we will see that many operations can run in $(\lg(n))$ we

Logarithmic time is not significantly worse than constant time:

$$\begin{aligned}\lg(1000) &\approx 10 \\ \lg(1\,000\,000) &\approx 20 \\ \lg(1\,000\,000\,000) &\approx 30 \\ \lg(1\,000\,000\,000\,000) &\approx 40 \\ \lg(1000^n) &\approx 10 n\end{aligned}$$

kB
MB
GB
TB

THERE'S BEEN A LOT OF CONFUSION OVER 1024 VS 1000, KBYTE VS KBIT, AND THE CAPITALIZATION FOR EACH. HERE, AT LAST, IS A SINGLE, DEFINITIVE STANDARD:

SYMBOL	NAME	SIZE	NOTES
kB	KILOBYTE	1024 BYTES OR 1000 BYTES	1000 BYTES DURING LEAP YEARS, 1024 OTHERWISE
KB	KELLY-BOOTLE STANDARD UNIT	1012 BYTES	COMPROMISE BETWEEN 1000 AND 1024 BYTES
KiB	IMAGINARY KILOBYTE	1024 $\sqrt{2}$ BYTES	USED IN QUANTUM COMPUTING
kb	INTEL KILOBYTE	1023.937528 BYTES	CALCULATED ON PENTIUM FPU.
Kb	DRIVEMAKER'S KILOBYTE	CURRENTLY 908 BYTES	SHRINKS BY 4 BYTES EACH YEAR FOR MARKETING REASONS
KBa	BAKER'S KILOBYTE	1152 BYTES	9 BITS TO THE BYTE SINCE YOU'RE SUCH A GOOD CUSTOMER

Application: Ropes

In 1995, Boehm *et al.* introduced the idea of a rope, or a *heavyweight* string



Application: Ropes

Alpha-numeric data is stored using a *string* of characters

- A character (or **char**) is a numeric value from 0 to 255 where certain numbers represent certain letters

For example,

‘A’ 65 01000001_2

‘B’ 66 01000010_2

‘a’ 97 01100001_2

‘b’ 98 01100010_2

‘ ’ 32 00100000_2

Unicode extends character encoding beyond the Latin alphabet

- Still waiting for the Tengwar characters... 

Íwëjëm n yéhëm i tñywa! 

Application: Ropes

A C-style string is an array of characters followed by the character with a numeric value of 0

```
char * story = "In a hole there lived a hobbit.;"
```

story → 

One problem with using arrays is the runtime required to concatenate two strings

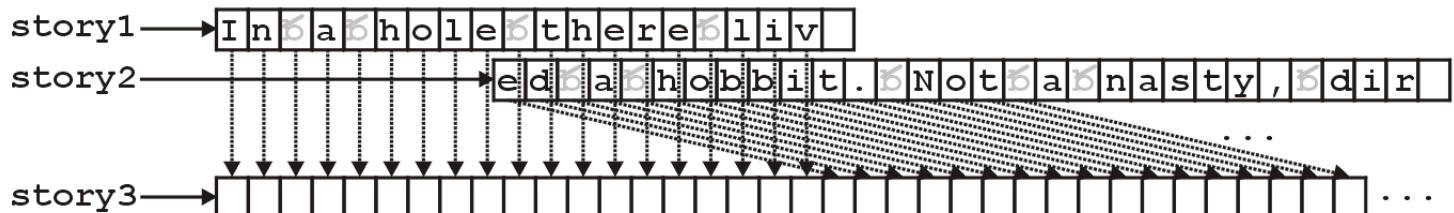


Application: Ropes

Concatenating two strings requires the operations of:

- Allocating more memory, and
- Copying both strings $(n + m)$

```
char * story1 = "In a hole there liv";
char * story2 = "ed a hobbit. Not a nasty, di";
```

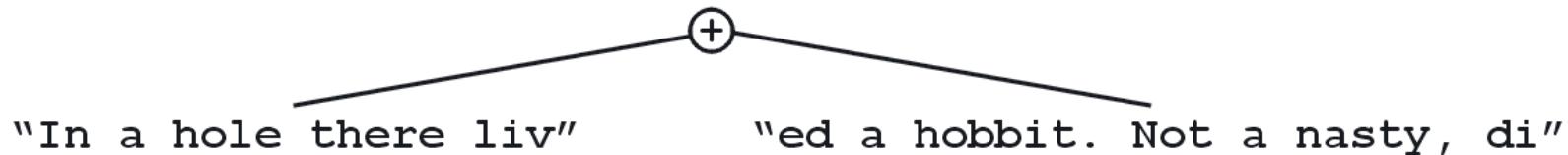


Application: Ropes

The rope data structure:

- Stores strings in the leaves,
- Internal nodes (full) represent the concatenation of the two strings, and
- Represents the string with the right sub-tree concatenated onto the end of the left

The previous concatenation may now occur in (1) time

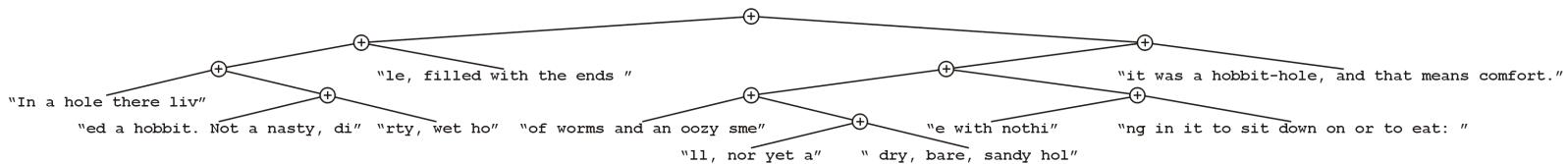


Application: Ropes

The string

"In a hole there lived a hobbit. Not a nasty, dirty, wet hole,
filled with the ends of worms and an oozy smell, nor yet a dry, bare,
sandy hole with nothing in it to sit down on or to eat: it was a
hobbit-hole, and that means comfort."

may be represented using the rope



References: [http://en.wikipedia.org/wiki/Rope_\(computer_science\)](http://en.wikipedia.org/wiki/Rope_(computer_science))
J.R.R. Tolkien, *The Hobbit*



Application: Ropes

Additional information may be useful:

- Recording the number of characters in both the left and right sub-trees

It is also possible to eliminate duplication of common sub-strings

"In a **hole** there lived a **hobbit**. Not a nasty, dirty, wet **hole**,
filled with the ends of worms and an oozy smell, nor yet a dry, bare,
sandy **hole** with nothing in **it** to sit down on or to eat: **it** was a
hobbit-hole, and that means comfort."

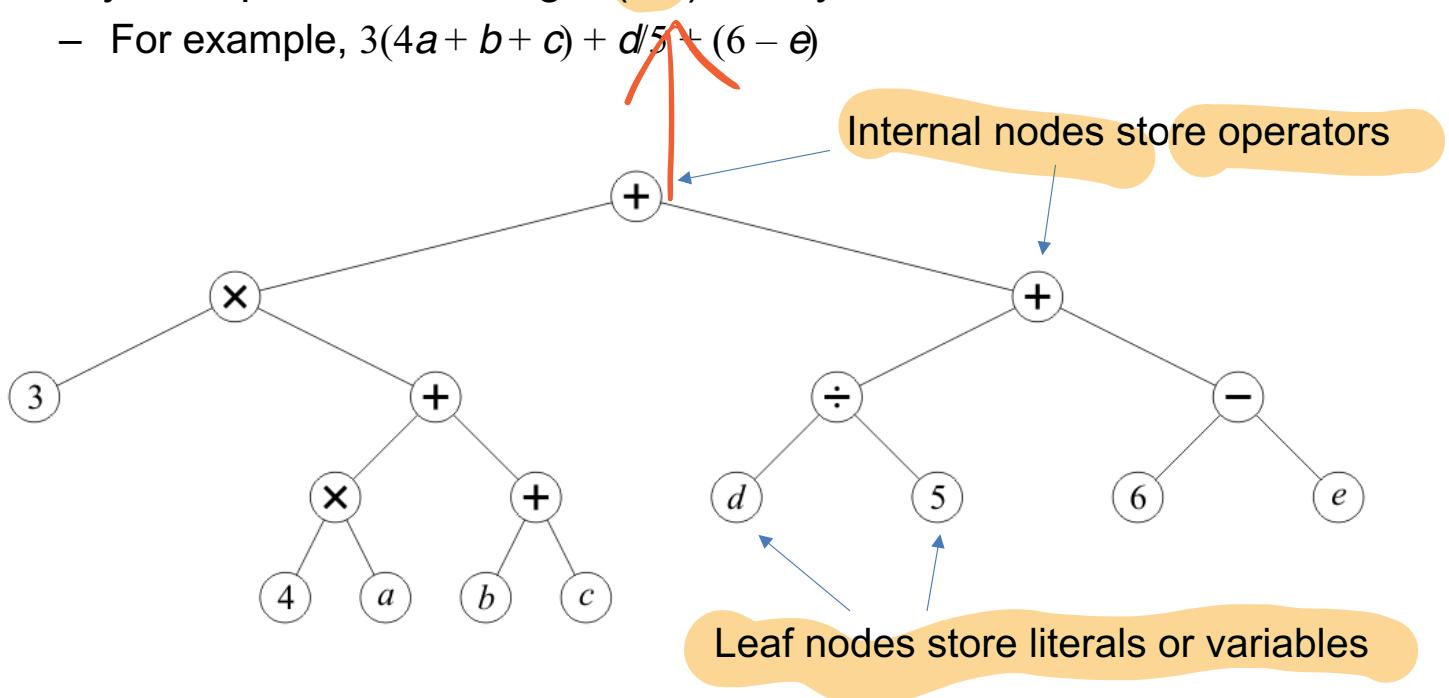
References: [http://en.wikipedia.org/wiki/Rope_\(computer_science\)](http://en.wikipedia.org/wiki/Rope_(computer_science))
J.R.R. Tolkien, *The Hobbit*



Application: Expression Trees

Any basic mathematical expression containing binary operators may be represented using a (full) binary tree

- For example, $3(4a + b + c) + d/5 + (6 - e)$



Application: Expression Trees

Observations:

- Internal nodes store operators
- Leaf nodes store literals or variables
- No nodes have just one sub tree
- The order is not relevant for
 - Addition and multiplication (commutative)
- Order is relevant for
 - Subtraction and division (non-commutative)
- It is possible to replace non-commutative operators using the unary negation and inversion:

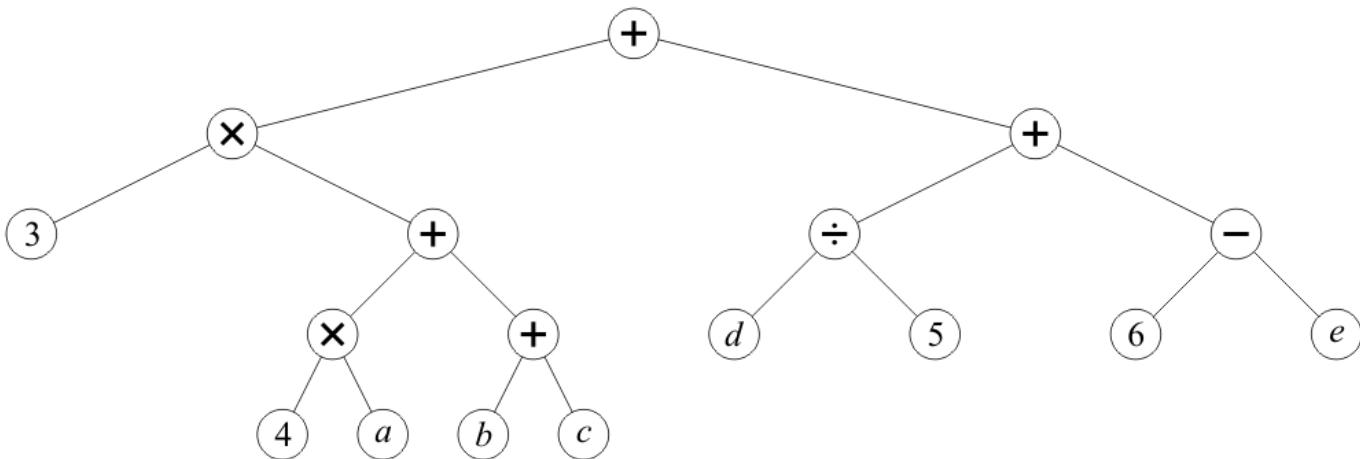
$$(a/b) = a b^{-1} \quad (a - b) = a + (-b)$$

Post Order

Application: Expression Trees

L, Right, Root

A post-order depth-first traversal converts such a tree to the reverse-Polish format



3 4 a × b c + + × d 5 ÷ 6 e - + +

Application: Expression Trees

Computers think in post-order:

- Both operands must be loaded into registers
- The operation is then called on those registers

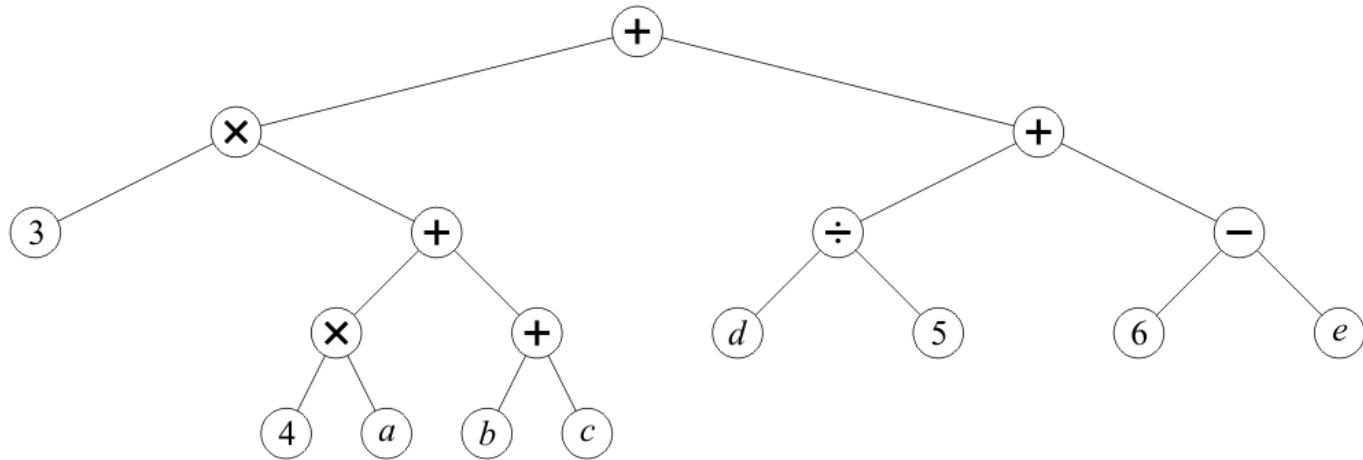
Humans think in in-order:

LEFT, Root, Right

- First, the left sub-tree is traversed
- Then, the current node is visited
- Finally, the right-sub-tree is traversed

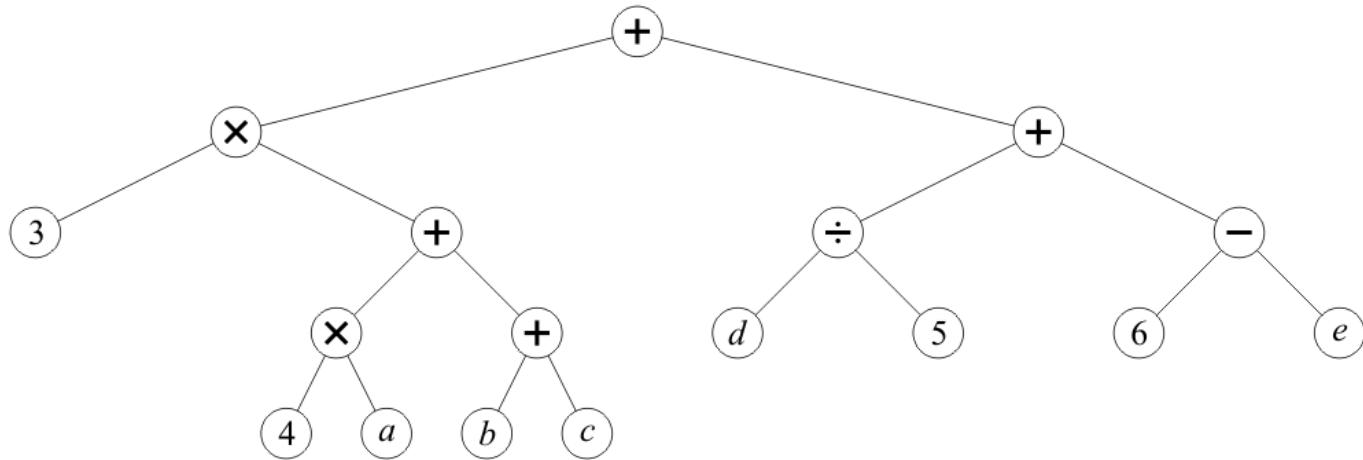
This is called an *in-order traversal*

In-order Traversal

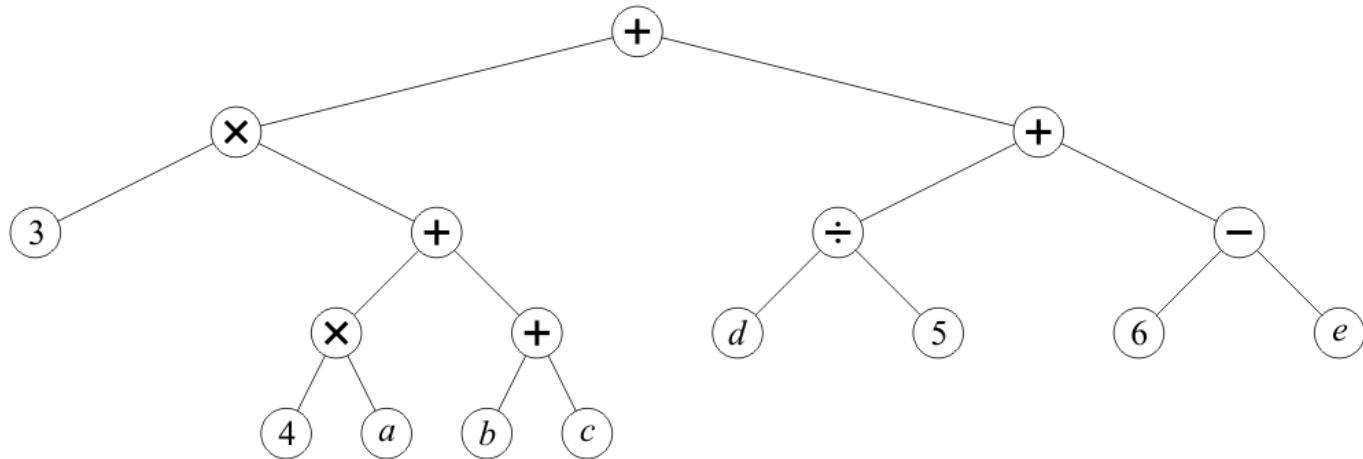


3

In-order Traversal

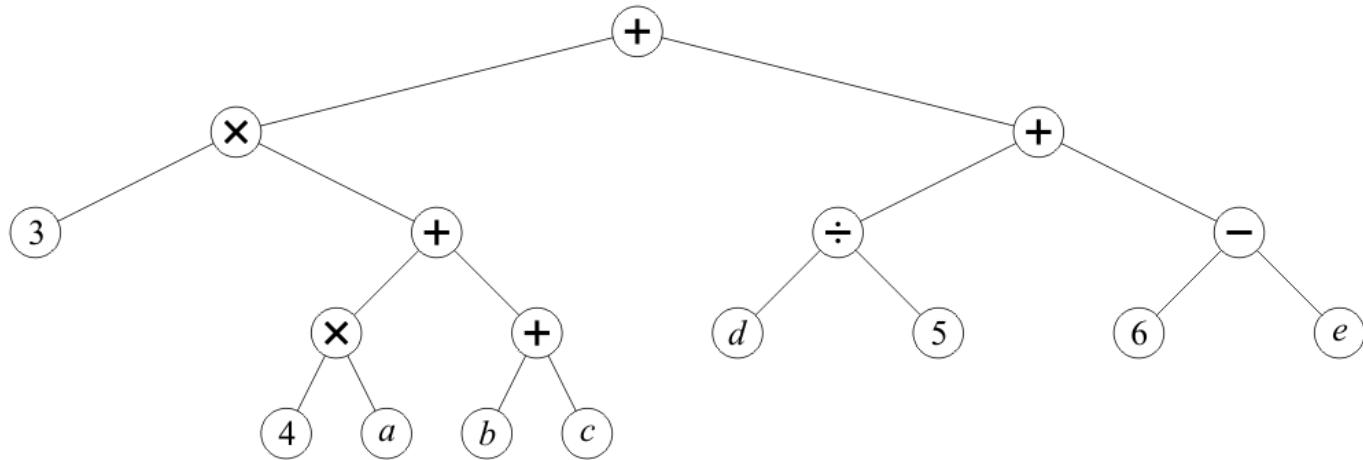


In-order Traversal



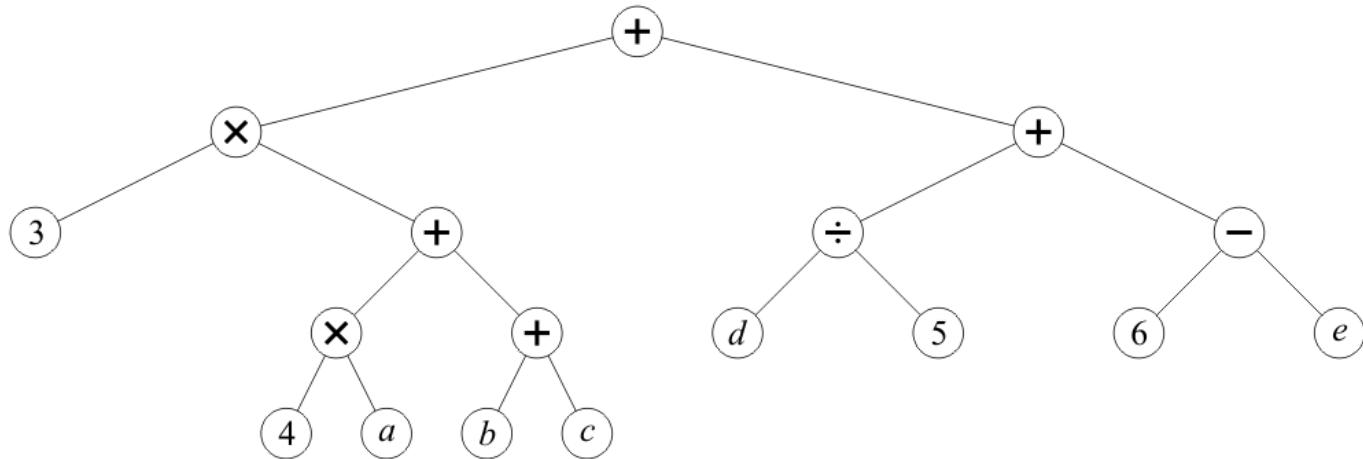
3×4

In-order Traversal



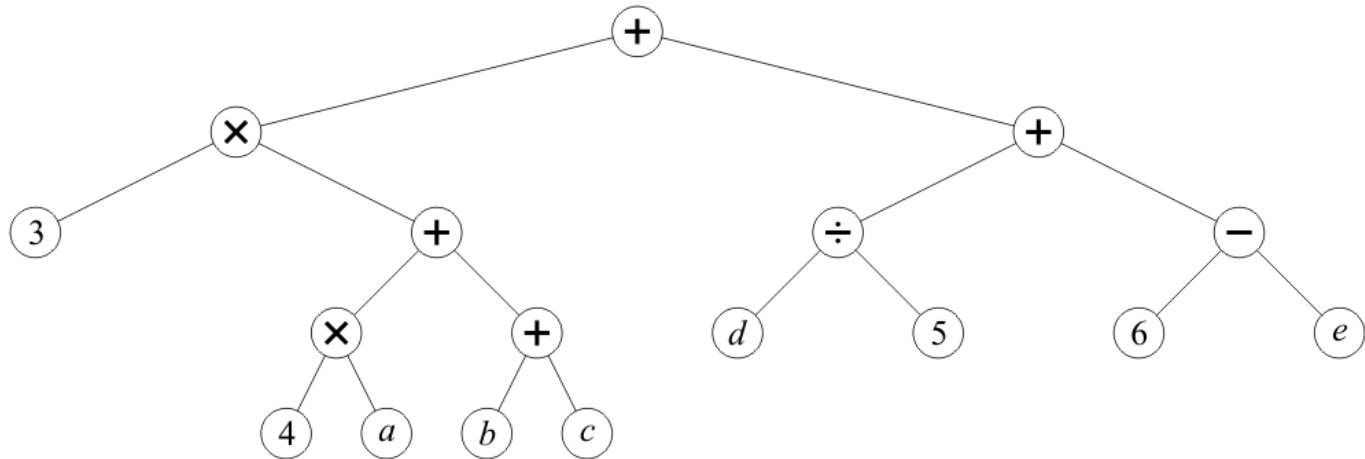
$3 \times 4 \times$

In-order Traversal



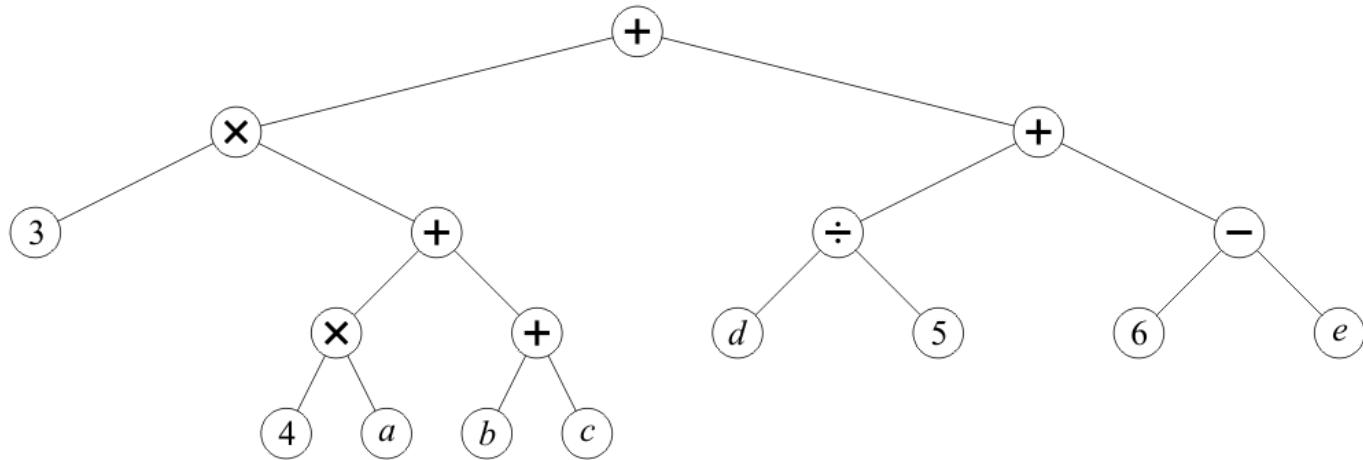
$3 \times 4 \times a$

In-order Traversal



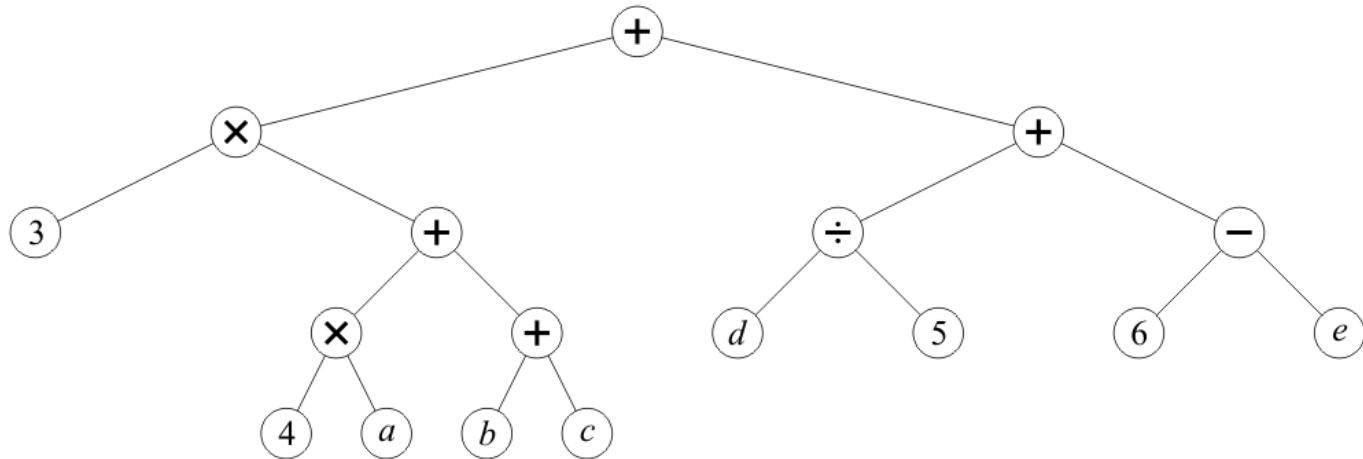
$3 \times 4 \times a +$

In-order Traversal



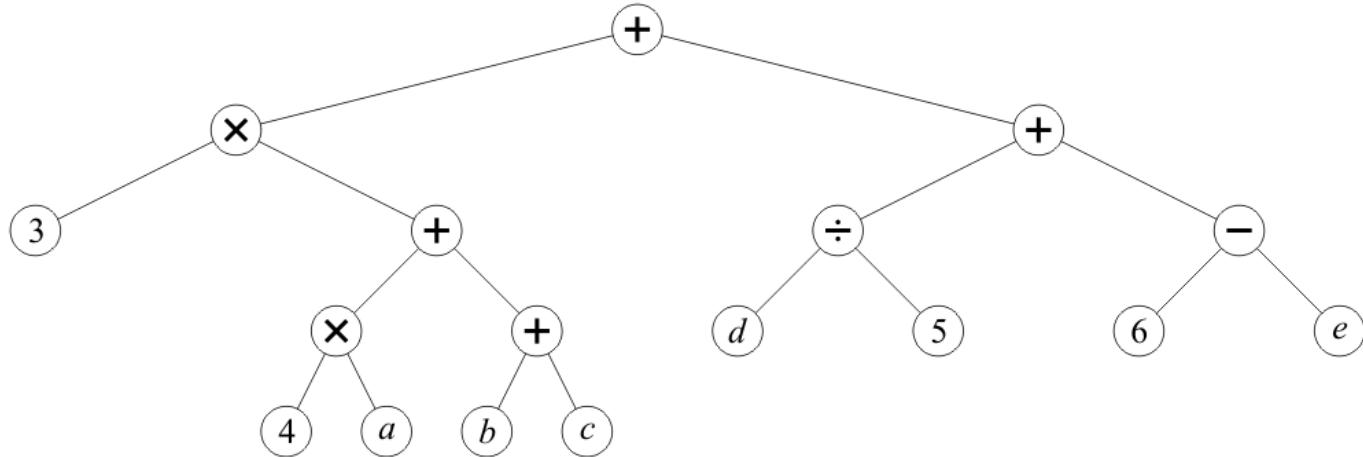
$$3 \times 4 \times a + b$$

In-order Traversal



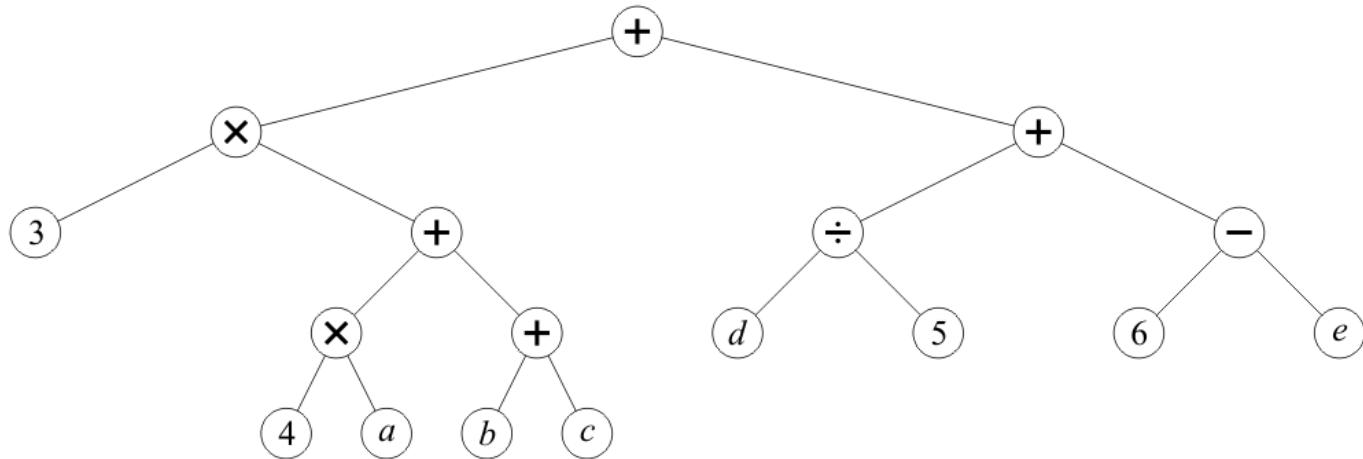
$3 \times 4 \times a + b +$

In-order Traversal



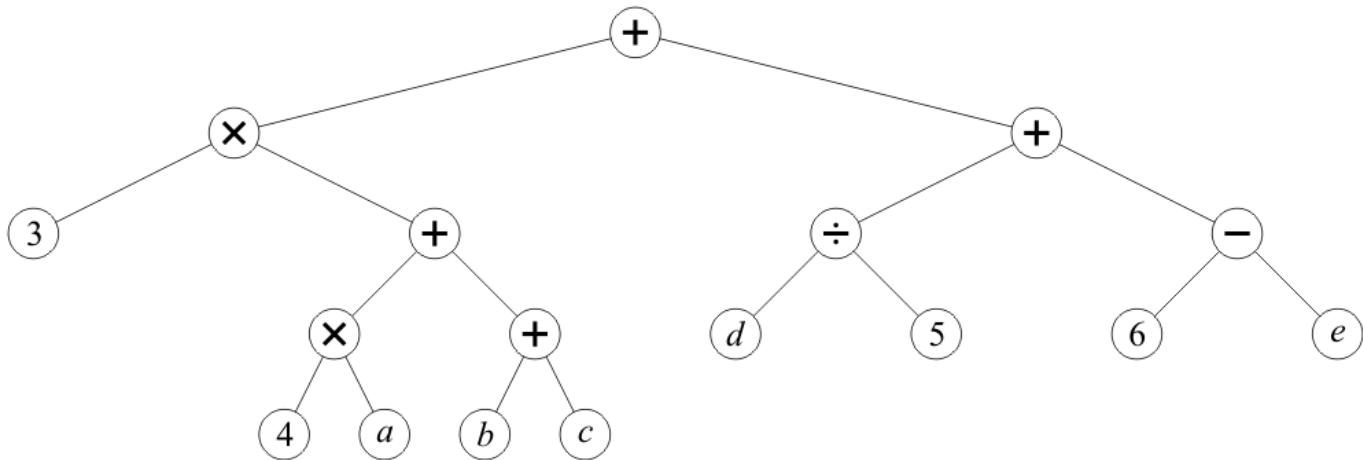
$$3 \times 4 \times a + b + c$$

In-order Traversal



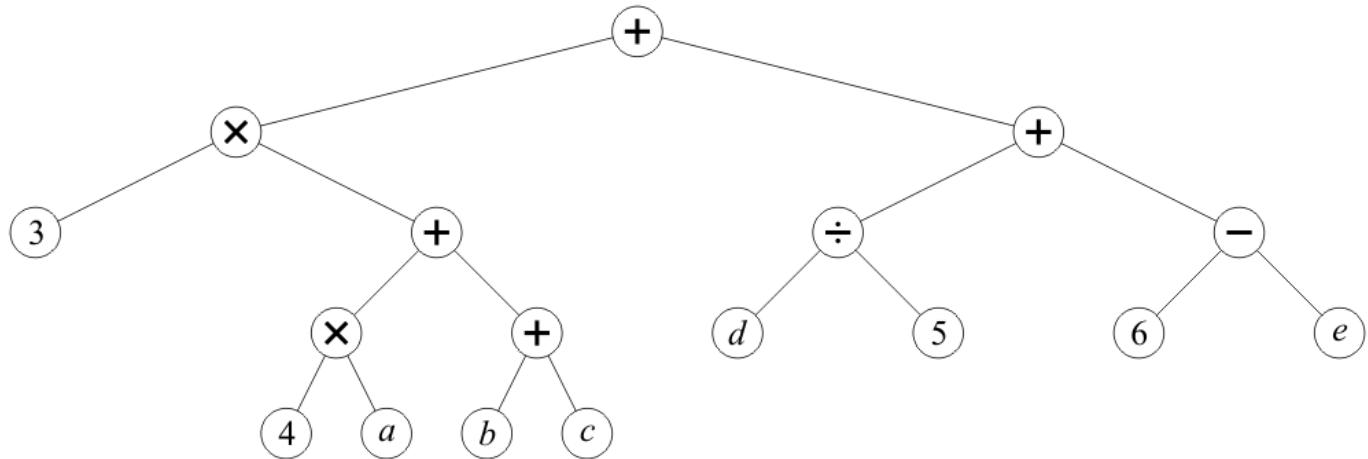
$3 \times 4 \times a + b + c +$

In-order Traversal



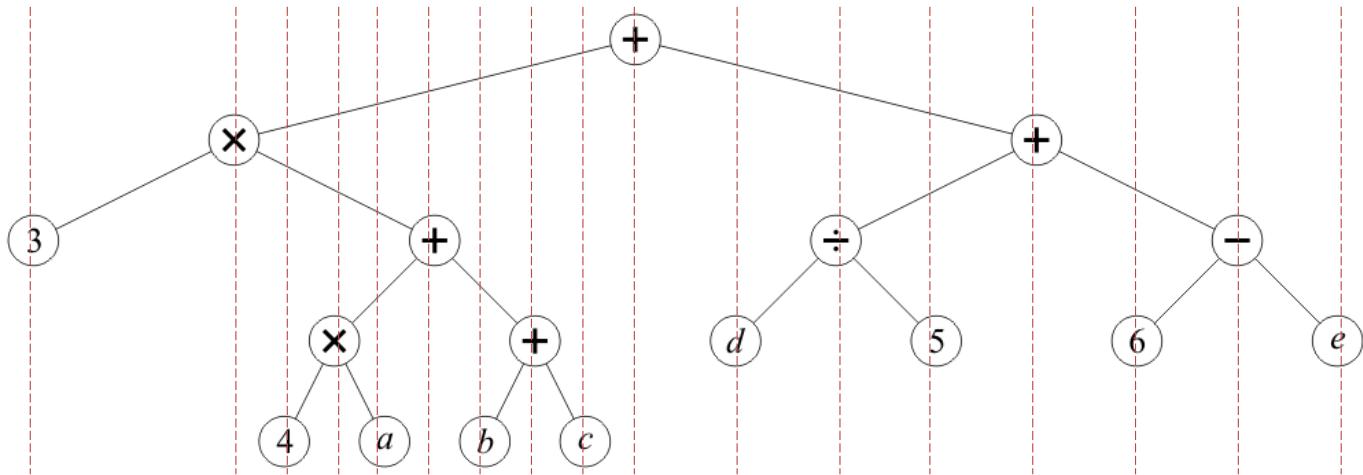
$$3 \times 4 \times a + b + c + d \div 5 + 6 - e$$

In-order Traversal



$$3 \times (4 \times a + (b + c)) + (d \div 5 + (6 - e))$$

In-order Traversal



$$3 \times 4 \times a + b + c + d \div 5 + 6 - e$$

Summary

In this talk, we introduced binary trees

- Each node has two distinct and identifiable sub-trees
- Either sub-tree may optionally be empty
- The sub-trees are ordered relative to the other

We looked at:

- Properties
- Applications

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Sincerely,

Douglas Wilhelm Harder, MMath

dwharder@alumni.uwaterloo.ca

Outline

- Binary tree
- Perfect binary tree
- Complete binary tree
- Left-child right-sibling binary tree

Outline

Introducing perfect binary trees

- Definitions and examples
- Number of nodes: $2^{h+1} - 1$
- Logarithmic height
- Number of leaf nodes: 2^h
- Applications

height = deep

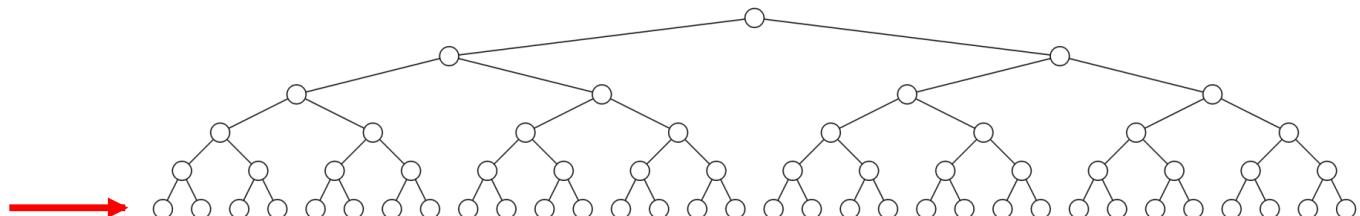
$$\frac{(1-2^{h+1})}{1-2}$$

$$(2^h-1)$$

Definition

Standard definition:

- A perfect binary tree of height h is a binary tree where
 - All leaf nodes have the same depth h
 - All other nodes are full



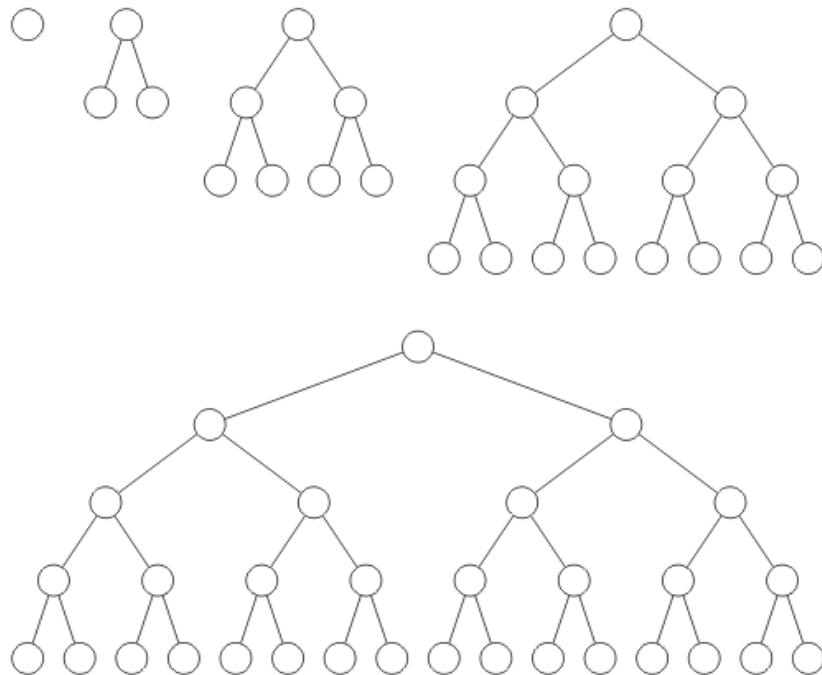
Definition

Recursive definition:

- A binary tree of height $h=0$ is perfect
- A binary tree with height $h>0$ is a perfect if both sub-trees are perfect
binary trees of height $h-1$

Examples

Perfect binary trees of height $h = 0, 1, 2, 3$ and 4



Examples

Perfect binary trees of height $h=3$ and $h=4$

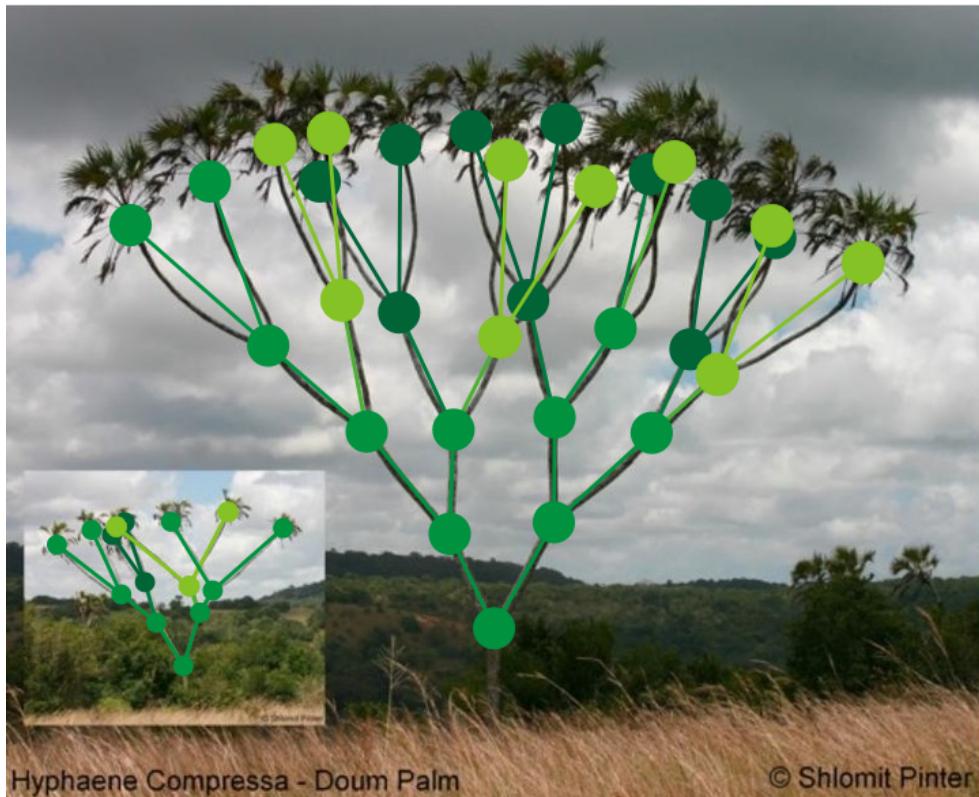


Hyphaene Compressa - Doum Palm

© Shlomit Pinter

Examples

Perfect binary trees of height $h=3$ and $h=4$



Hyphaene Compressa - Doum Palm

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Theorems

Four theorems of perfect binary trees:

- A perfect binary tree of height h has $2^{h+1} - 1$ nodes
- The height is $\Theta(\ln(n))$
- There are 2^h leaf nodes
- The average depth of a node is $\Theta(\ln(n))$

These theorems will allow us to determine the optimal run-time properties of operations on binary trees

$$2^{h+1} - 1 \text{ Nodes}$$

Theorem

A perfect binary tree of height h has $2^{h+1} - 1$ nodes

Proof:

We will use mathematical induction



$$2^{h+1} - 1 \text{ Nodes}$$

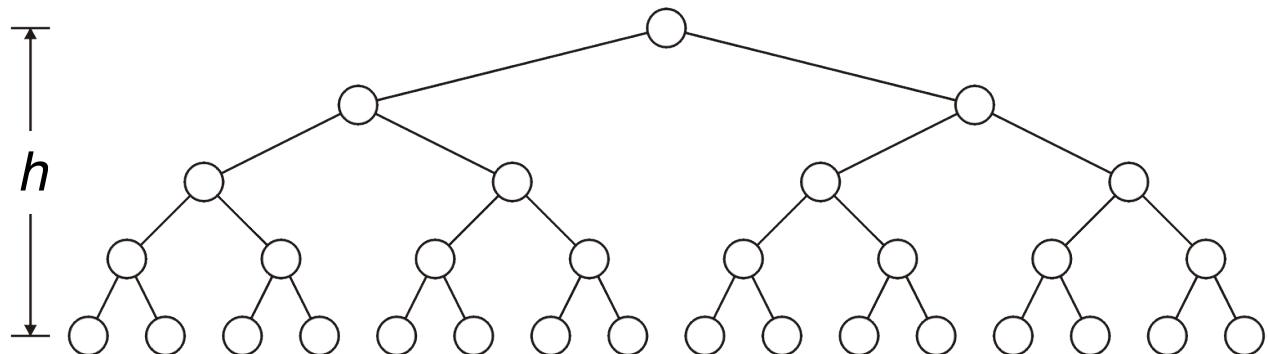
The base case:

- When $h=0$ we have a single node $n=1$
- The formula is correct: $2^{0+1} - 1 = 1$

$$2^{h+1} - 1 \text{ Nodes}$$

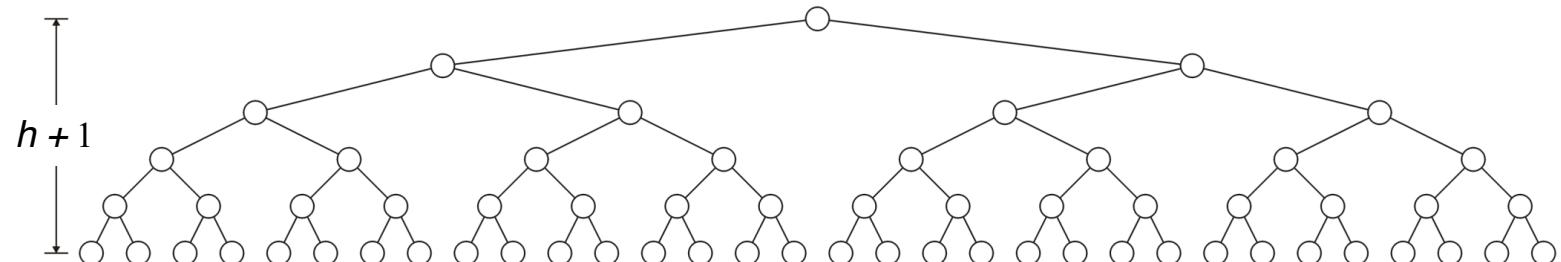
The inductive step:

- Assume that a tree of height h has $n = 2^{h+1} - 1$ nodes



$$2^{h+1} - 1 \text{ Nodes}$$

We must show that a tree of height $h + 1$ has
 $n = 2^{(h+1)+1} - 1 = 2^{h+2} - 1$ nodes

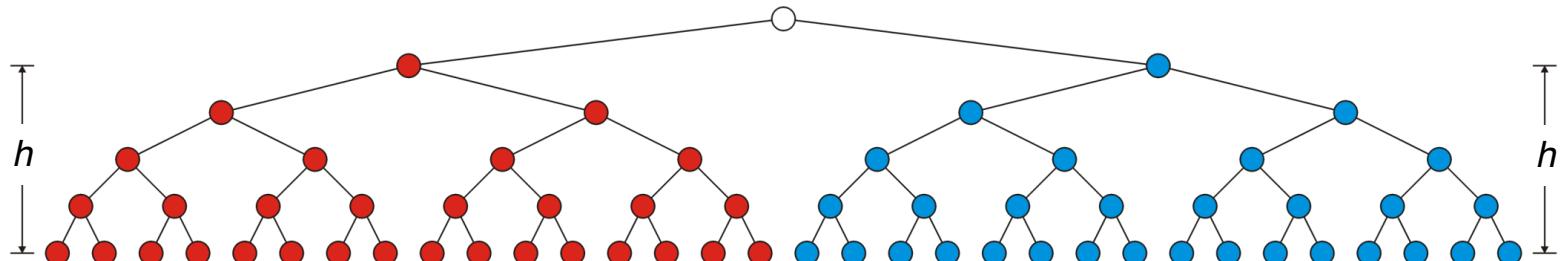


$$2^{h+1} - 1 \text{ Nodes}$$

Using the recursive definition, both sub-trees are perfect trees of height h

- By assumption, each sub-tree has $2^{h+1} - 1$ nodes
- Therefore the total number of nodes is

$$(2^{h+1} - 1) + 1 + (2^{h+1} - 1) = 2^{h+2} - 1$$



2 sub ·

$$2^{h+1} - 1 \text{ Nodes}$$

Consequently

The statement is true for $h=0$ and the truth of the statement for an arbitrary h implies the truth of the statement for $h+1$.

Therefore, by the process of mathematical induction, the statement is true for all $h \geq 0$

Logarithmic Height

Theorem

A perfect binary tree with n nodes has height $\lg(n+1) - 1$

Proof

Solving $n = 2^{h+1} - 1$ for h :

$$n + 1 = 2^{h+1}$$

$$\lg(n+1) = h + 1$$

$$h = \lg(n+1) - 1$$

Logarithmic Height

Lemma

$$\lg(n+1) - 1 = \Theta(\ln(n))$$

Proof

$$\lim_{n \rightarrow \infty} \frac{\lg(n+1) - 1}{\ln(n)} = \lim_{n \rightarrow \infty} \frac{(n+1)\ln(2)}{n\ln(n)\ln(2)\ln(2)} = \lim_{n \rightarrow \infty} \frac{1}{\ln(n)} = 0$$

(+)

Q.E.D.

2^h Leaf Nodes

Theorem

A perfect binary tree with height h has 2^h leaf nodes

Proof (by induction):

When $h = 0$, there is $2^0 = 1$ leaf node.

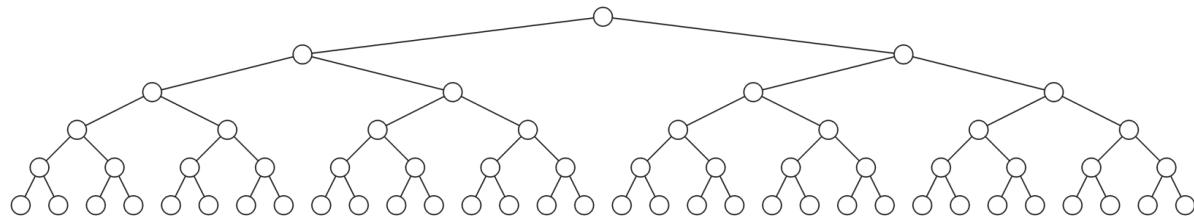
Assume that a perfect binary tree of height h has 2^h leaf nodes and observe that both sub-trees of a perfect binary tree of height $h + 1$ have 2^h leaf nodes.

Consequence: Over half of the nodes are leaf nodes:

$$\frac{2^h}{2^{h+1} - 1} > \frac{1}{2}$$

The Average Depth of a Node

The average depth of a node in a perfect binary tree is



Depth	Count
0	1
1	2
2	4
3	8
4	16
5	32

Sum of the depths

$$\sum_{k=0}^h k2^k = \frac{h2^{h+1} - 2^{h+1} + 2}{2^{h+1} - 1} = \frac{h(2^{h+1} - 1) - (2^{h+1} - 1) + 1 + h}{2^{h+1} - 1}$$
$$= h - 1 + \frac{h + 1}{2^{h+1} - 1} \approx h - 1 = \Theta(\ln(n))$$

Number of nodes

$n \rightarrow \infty$

Applications

Perfect binary trees are considered to be the *ideal* case

- The height and average depth are both $\mathcal{O}(\ln(n))$

We will attempt to find trees which are as close as possible to perfect binary trees

Perfect

idea

Summary

We have defined perfect binary trees and discussed:

- The number of nodes: $n = 2^{h+1} - 1$
- The height: $\lg(n+1) - 1$
- The number of leaves: 2^h
- Half the nodes are leaves
 - Average depth is $(\ln(n))$
- It is an ideal case

$$\lg(n+1) - 1$$

+ |

- |

Outline

- Binary tree
- Perfect binary tree
- Complete binary tree
- Left-child right-sibling binary tree

Outline

Introducing complete binary trees

- Background
- Definitions
- Examples
- Logarithmic height
- Array storage

Background

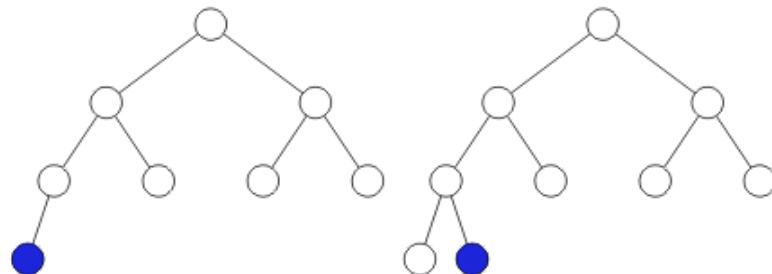
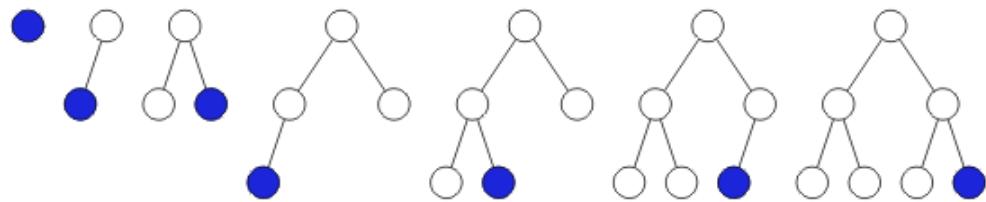
We require binary trees which are

- Similar to perfect binary trees, but
- Defined for any number of nodes

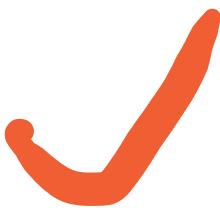
Definition

A complete binary tree filled at each depth from left to right

- Identical order to that of a breadth-first traversal

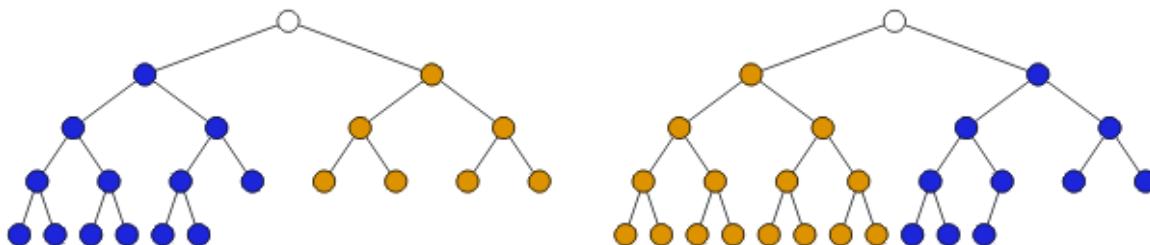


Recursive Definition



Recursive definition: a binary tree with a single node is a complete binary tree of height $h=0$ and a complete binary tree of height h is a tree where either:

- The left sub-tree is a **complete tree** of height $h-1$ and the right sub-tree is a **perfect tree** of height $h-2$, or
- The left sub-tree is **perfect tree** with height $h-1$ and the right sub-tree is **complete tree** with height $h-1$



Height

Theorem

The height of a complete binary tree with n nodes is $h = \lfloor \lg(n) \rfloor$

Proof:

Perfect. $\lfloor \lg(n+1) - 1 \rfloor$

– Base case:

- When $n = 1$ then $\lfloor \lg(1) \rfloor = 0$ and a tree with one node is a complete tree with height $h = 0$

– Inductive step:

- Assume that a complete tree with n nodes has height $\lfloor \lg(n) \rfloor$
- Must show that $\lfloor \lg(n+1) \rfloor$ gives the height of a complete tree with $n+1$ nodes
- Two cases:
 - If the tree with n nodes is perfect, and
 - If the tree with n nodes is complete but not perfect

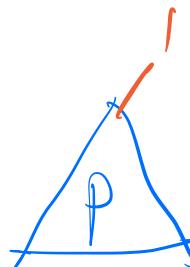
Height

Case 1 (the tree with n nodes is perfect):

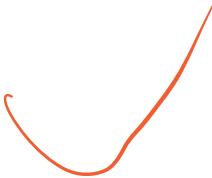
- If it is a perfect tree then
 - It had $n = 2^{h+1} - 1$ nodes
 - Adding one more node must increase the height
- So the tree with $n+1$ nodes has height $h+1$ and we have:

$$\lfloor \lg(n+1) \rfloor = \lfloor \lg(2^{h+1} - 1 + 1) \rfloor = \lfloor \lg(2^{h+1}) \rfloor = h+1$$

$$\lfloor \lg(h+1) - 1 + 1 \rfloor = h+1$$



Height



Case 2 (the tree with n nodes is complete but not perfect):

- If it is not a perfect tree then

not perfect $2^h \leq n < 2^{h+1} - 1$
 $2^h + 1 \leq n + 1 < 2^{h+1}$

$$h < \lg(2^h + 1) \leq \lg(n + 1) < \lg(2^{h+1}) = h + 1$$

$$h \leq \lfloor \lg(2^h + 1) \rfloor \leq \lfloor \lg(n + 1) \rfloor < h + 1$$

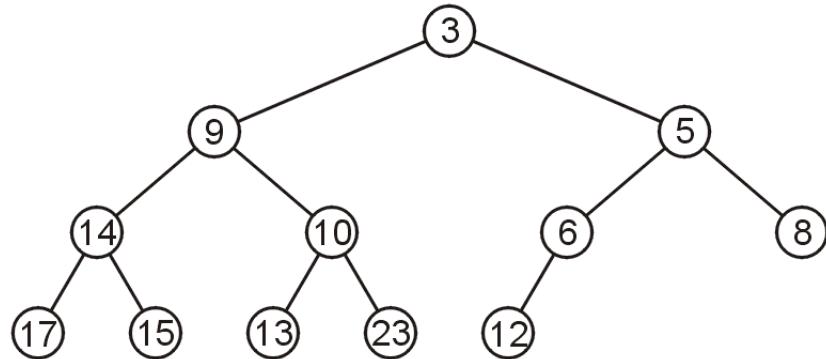
- So the tree with $n+1$ nodes has height h and we have $\lfloor \lg(n + 1) \rfloor = h$

By mathematical induction, the statement must be true for all $n \geq 1$

Array storage

We are able to store a complete tree as an array

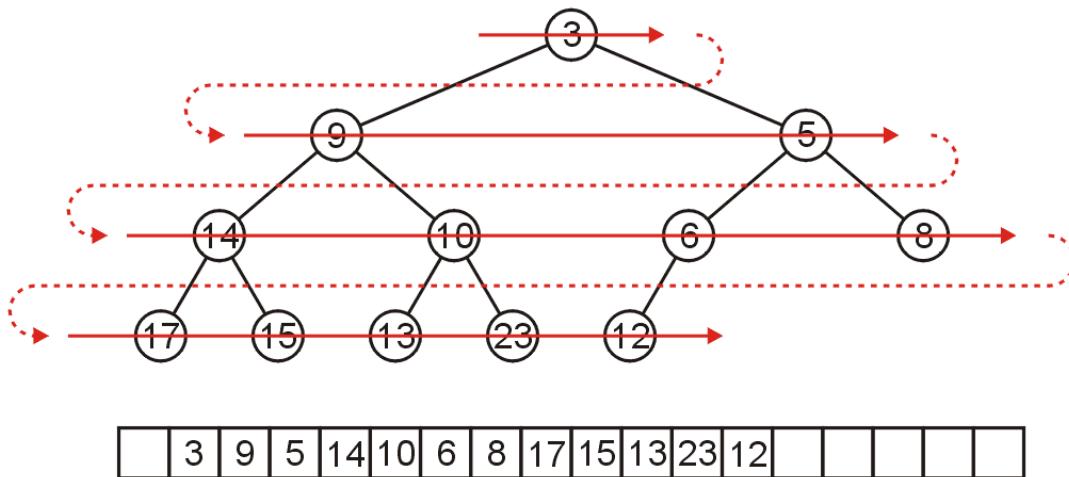
- Traverse the tree in breadth-first order, placing the entries into the array



Array storage

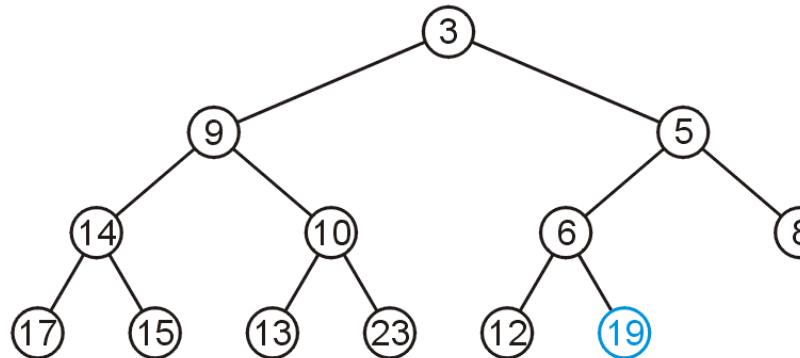
We are able to store a complete tree as an array

- Traverse the tree in breadth-first order, placing the entries into the array



Array storage

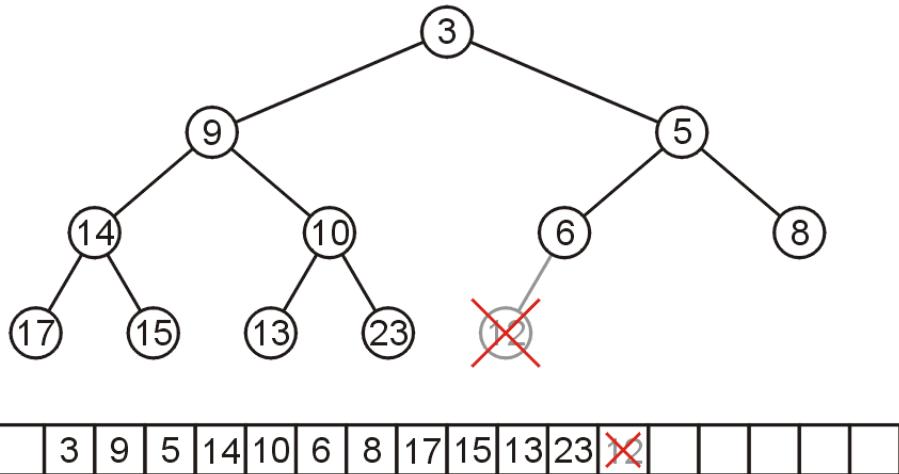
To insert another node while maintaining the complete-binary-tree structure, we must insert into the next array location



	3	9	5	14	10	6	8	17	15	13	23	12	19				
--	---	---	---	----	----	---	---	----	----	----	----	----	----	--	--	--	--

Array storage

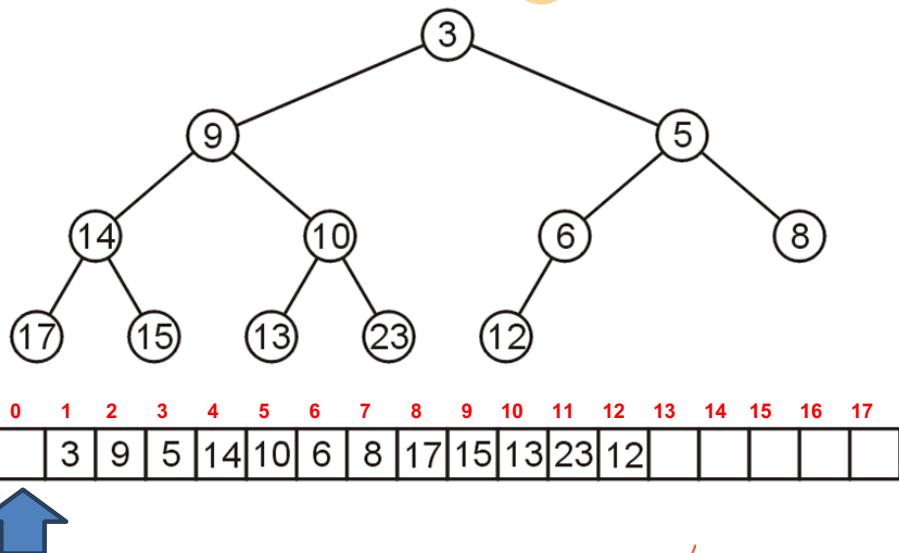
To remove a node while keeping the complete-tree structure, we must remove the last element in the array



Array storage

Leaving the first entry blank yields a bonus:

- The children of the node with index k are in $2k$ and $2k+1$
- The parent of node with index k is in $k \div 2$

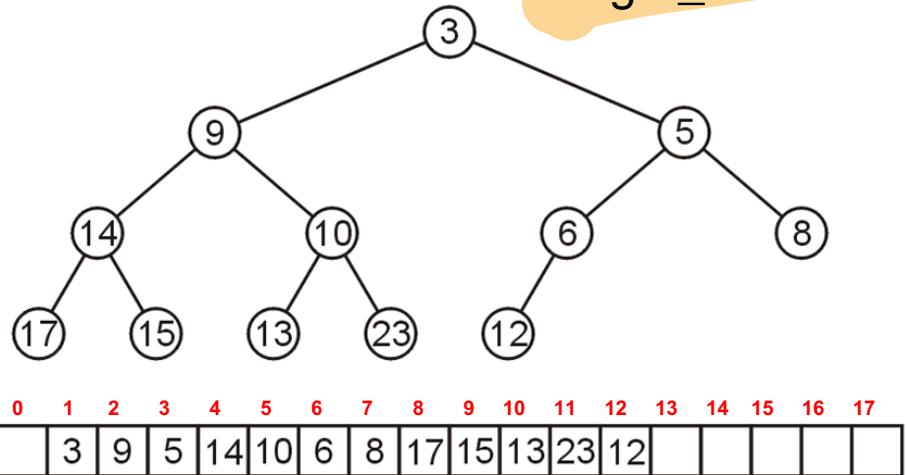


Parent - children
index .

Array storage

Leaving the first entry blank yields a bonus:

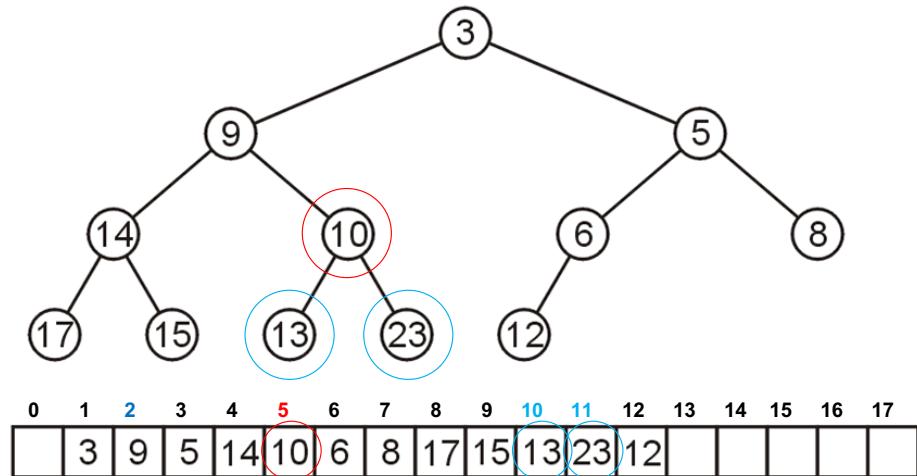
- In C++, this simplifies the calculations:
`parent = k >> 1;
left_child = k << 1;
right_child = left_child | 1;`



Array storage

For example, node 10 has index 5:

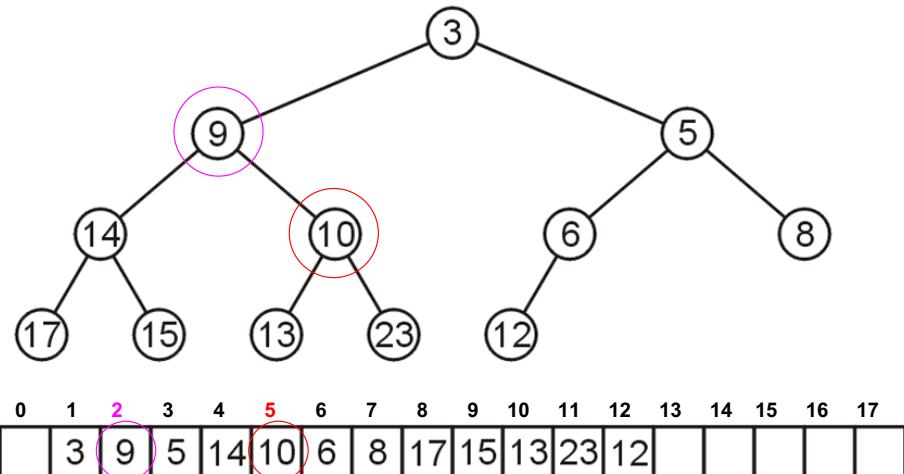
- Its children 13 and 23 have indices 10 and 11, respectively



Array storage

For example, node 10 has index 5:

- Its children 13 and 23 have indices 10 and 11, respectively
- Its parent is node 9 with index $5/2 = 2$



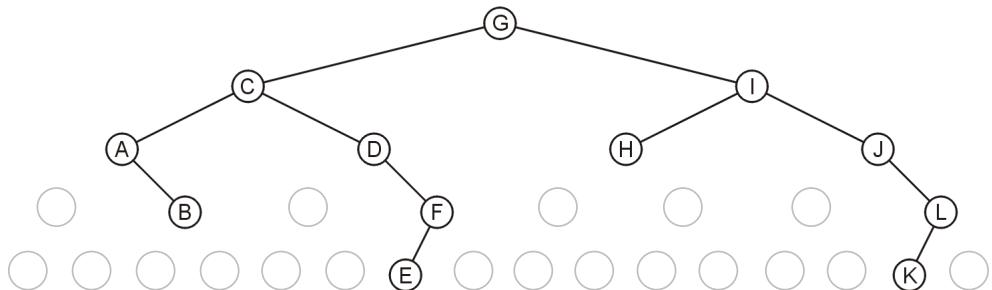
Array storage

Question: why not store any binary tree as an array in this way?

- There is a significant potential for a lot of wasted memory

Consider this tree with 12 nodes would require an array of size 32

- Adding a child to node K doubles the required memory

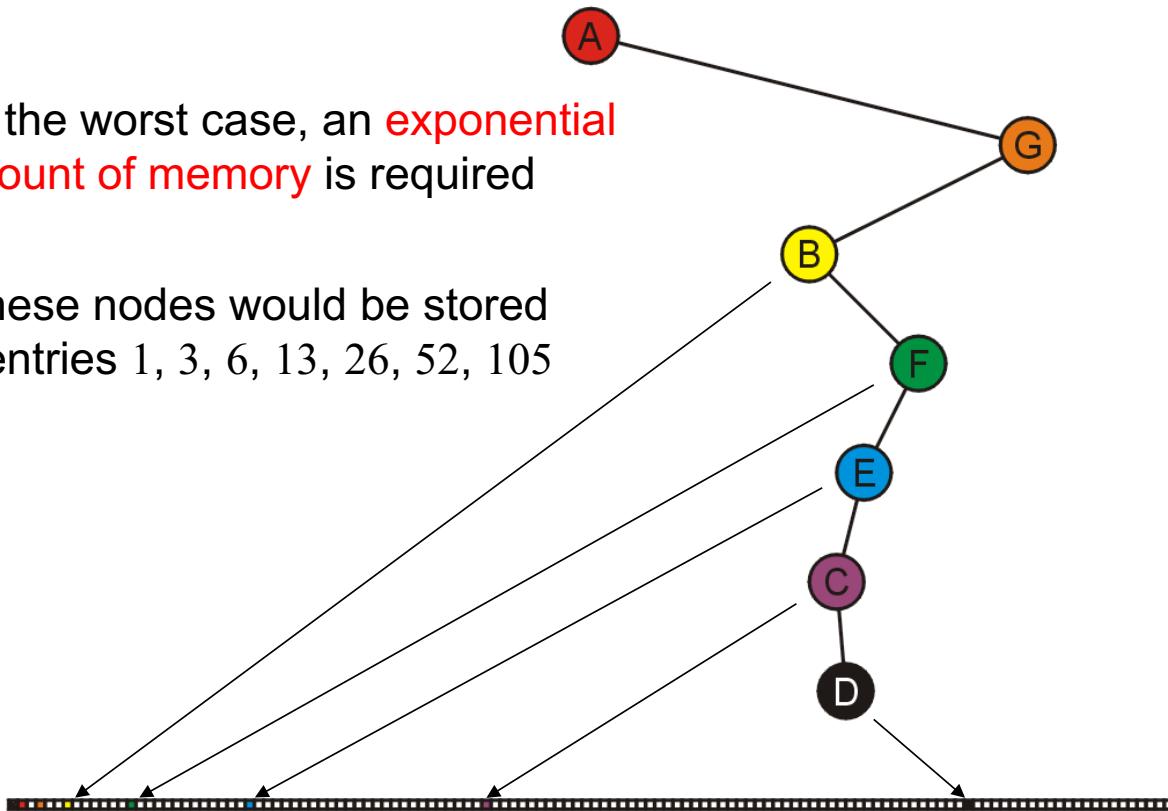


✗	G	C	I	A	D	H	J	B	F			L					E				K
---	---	---	---	---	---	---	---	---	---	--	--	---	--	--	--	--	---	--	--	--	---

Array storage

In the worst case, an **exponential amount of memory** is required

These nodes would be stored in entries 1, 3, 6, 13, 26, 52, 105



Summary

In this topic, we have covered the concept of a complete binary tree:

- A useful relaxation of the concept of a perfect binary tree
- It has a compact array representation

Outline

- Binary tree
- Perfect binary tree
- Complete binary tree
- **Left-child right-sibling binary tree**

Background

Our simple tree data structure is node-based where children are stored as a linked list

- Is it possible to store a general tree as a binary tree?

The Idea

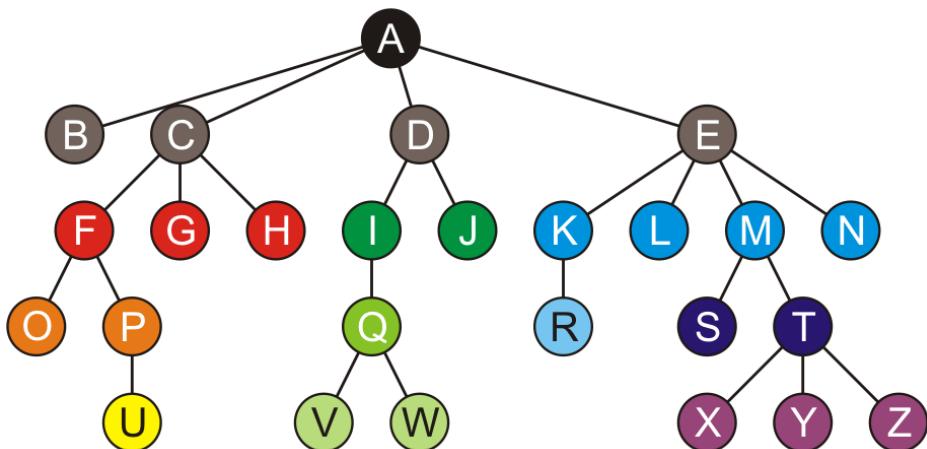
Consider the following:

- The first child of each node is its left sub-tree
- The next sibling of each node is in its right sub-tree

This is called a left-child—right-sibling binary tree

Example

Consider this general tree

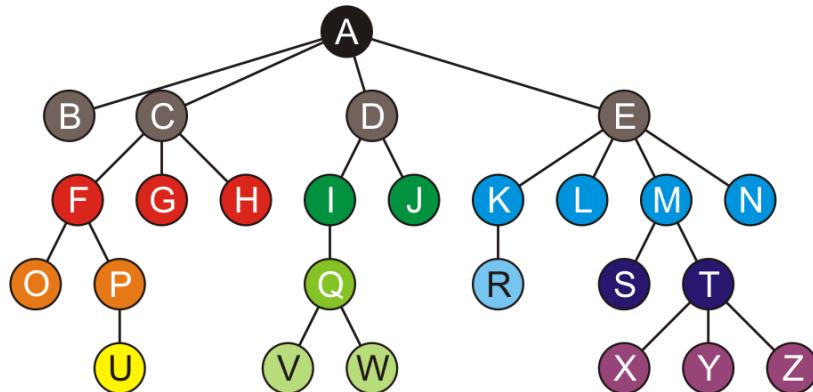
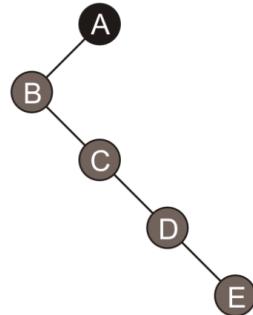


Example

B, the first child of A, is the left child of A

For the three siblings C, D, E:

- C is the right sub-tree of B
- D is the right sub-tree of C
- E is the right sub-tree of D



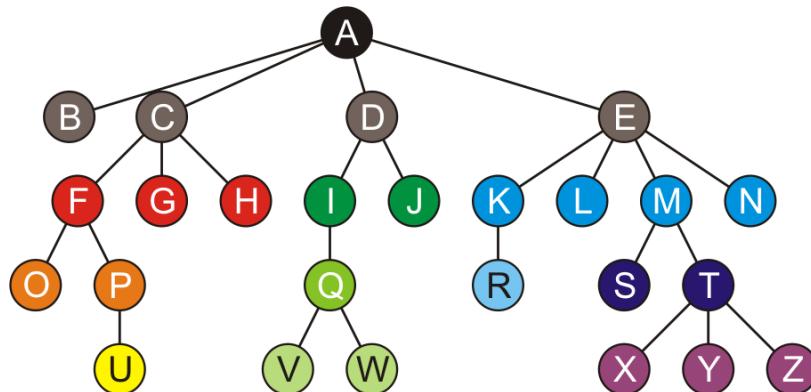
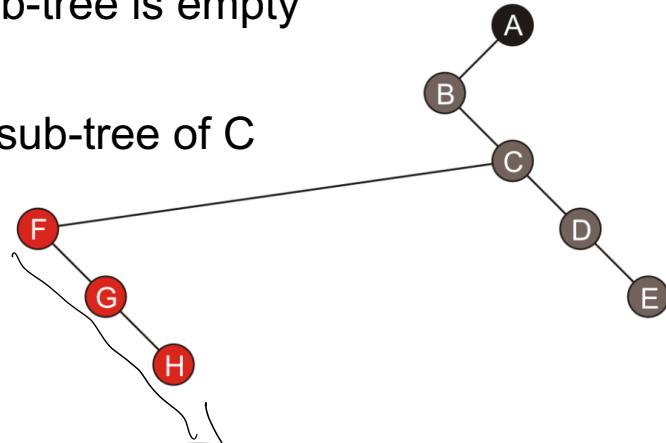
Example

B has no children, so its left sub-tree is empty

F, the first child of C, is the left sub-tree of C

For the next two siblings:

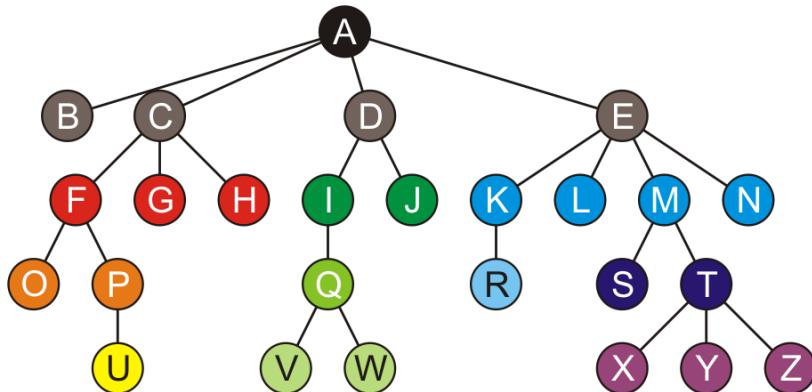
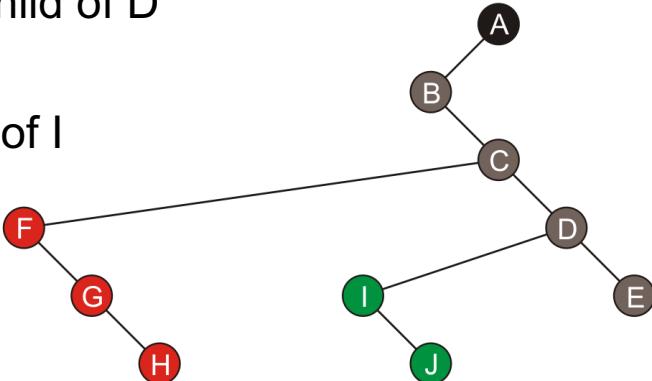
- G is the right sub-tree of F
- H is the right sub-tree of G



Example

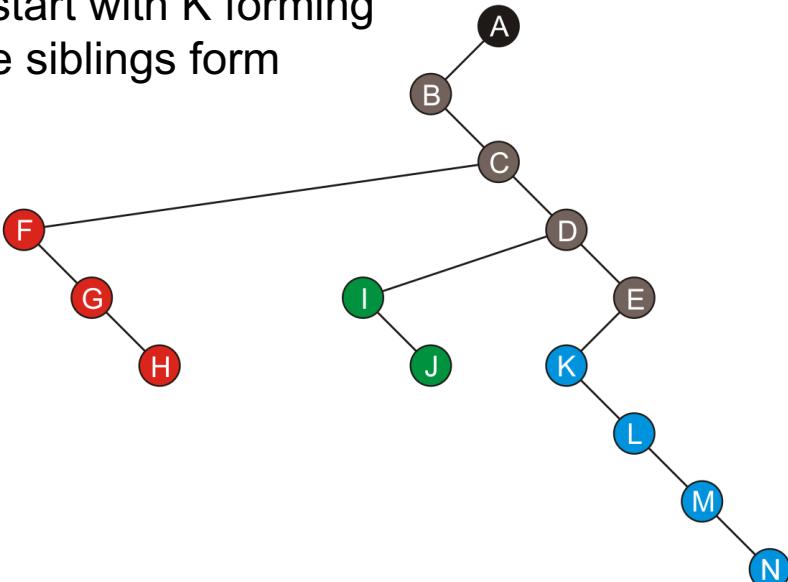
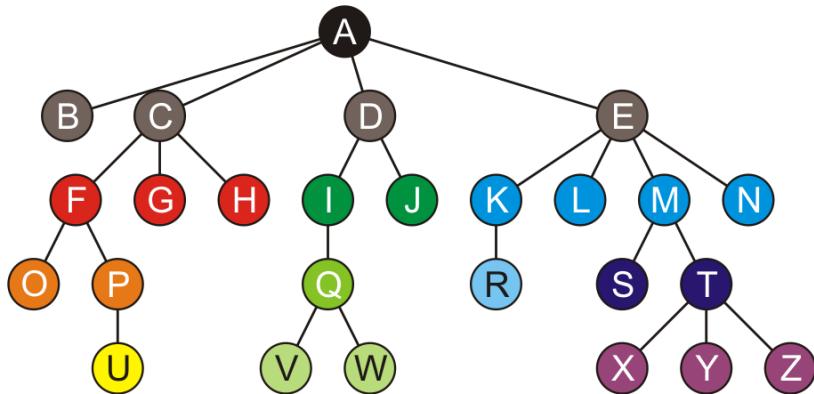
I, the first child of D, is the left child of D

Its sibling J is the right sub-tree of I

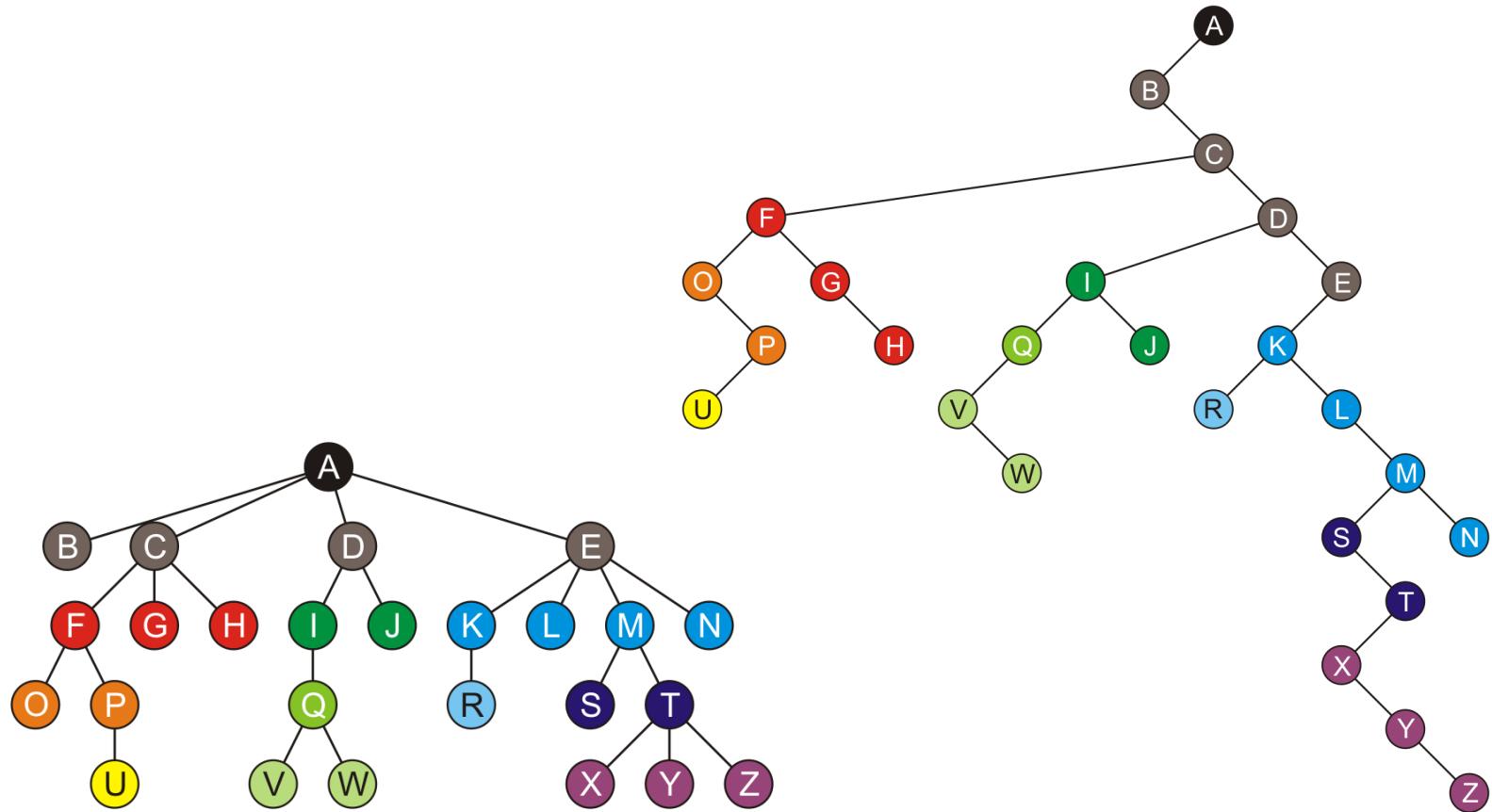


Example

Similarly, the four children of E start with K forming the left sub-tree of E and its three siblings form a chain along the right sub-trees

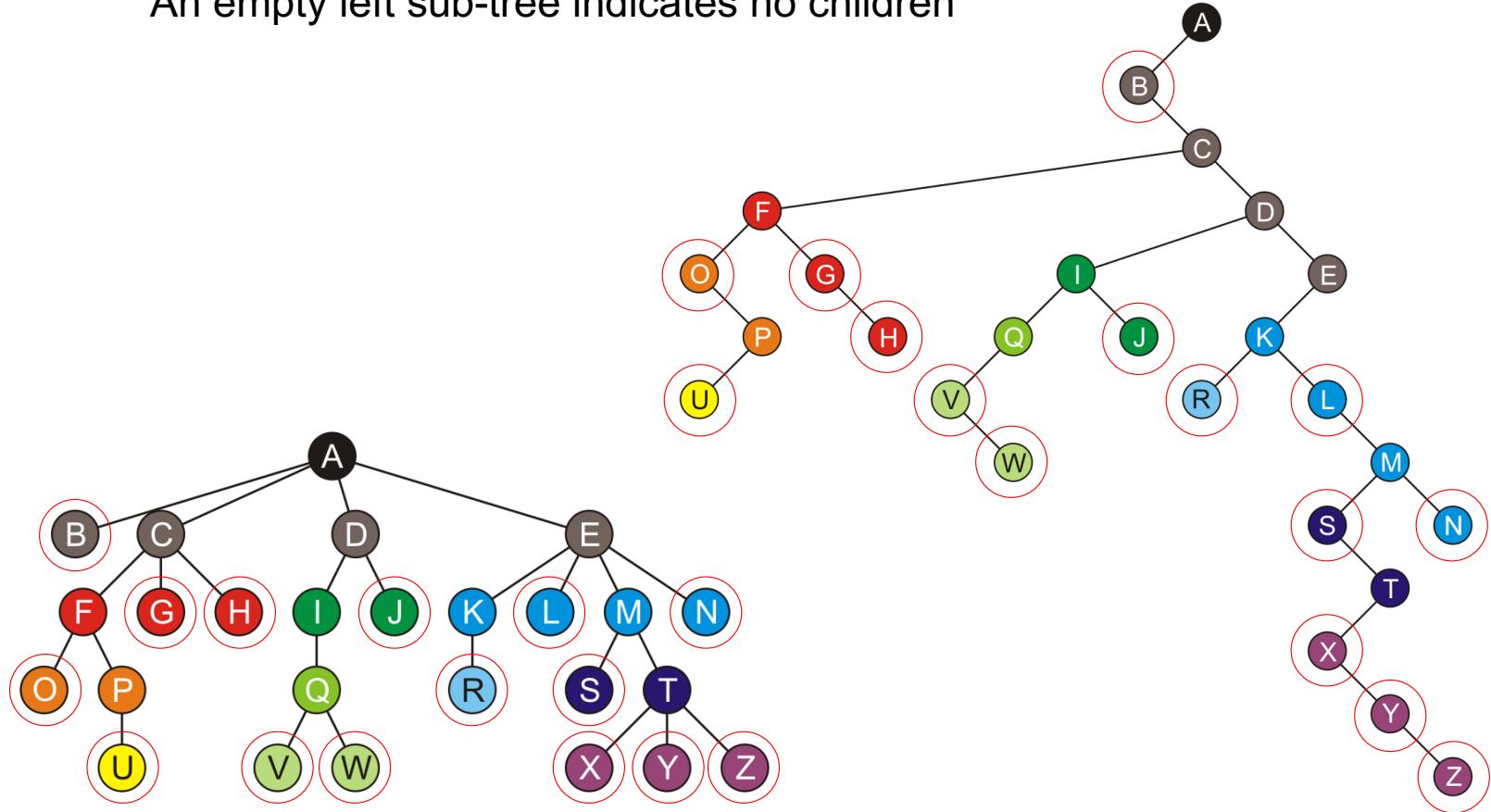


Example



Example

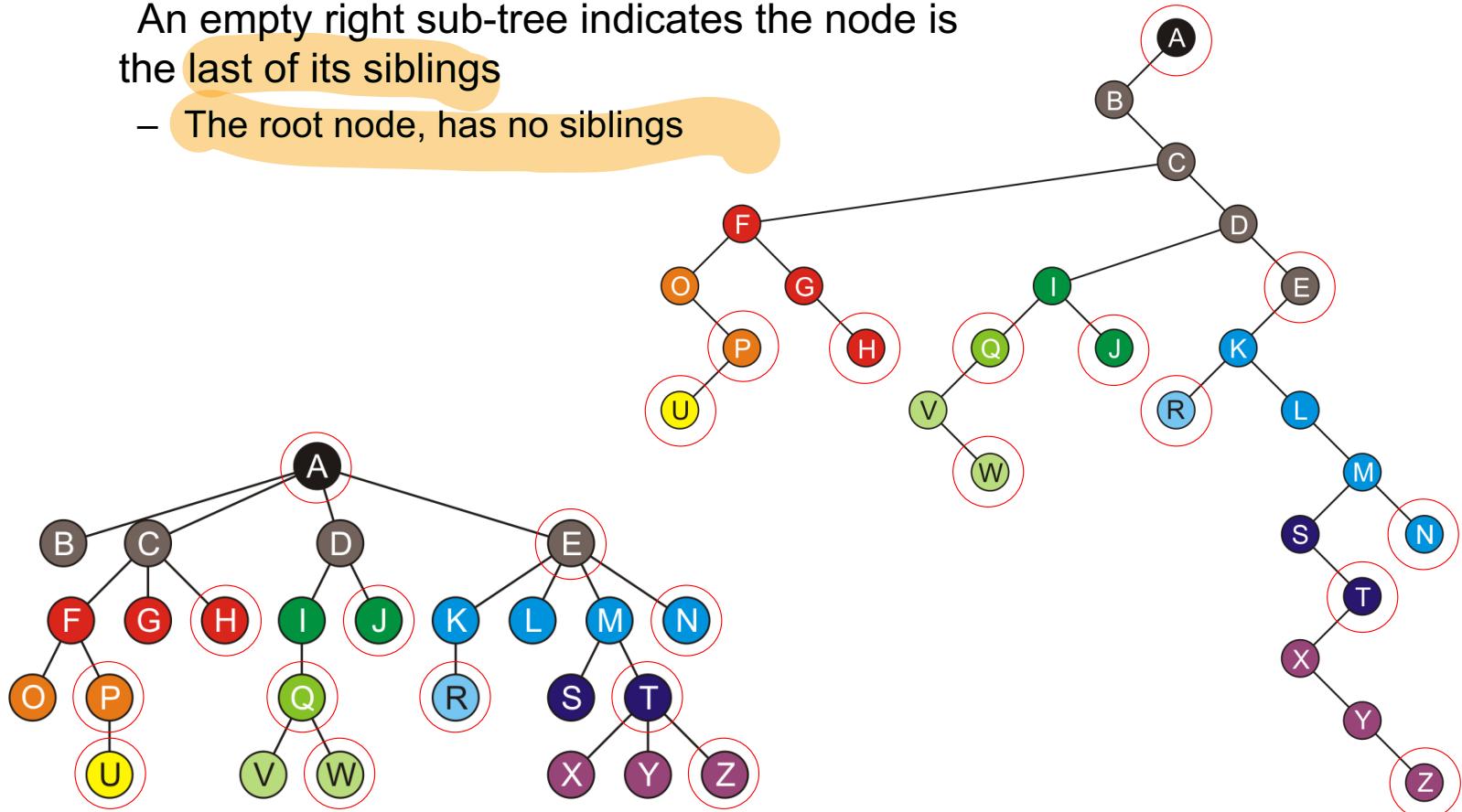
An empty left sub-tree indicates no children



Example

An empty right sub-tree indicates the node is
the last of its siblings

- The root node, has no siblings



Transformation

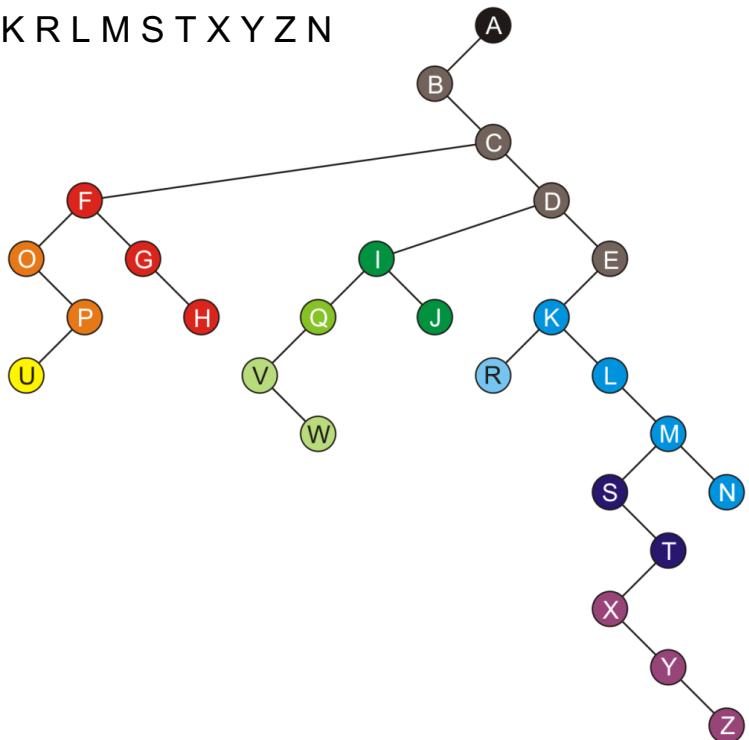
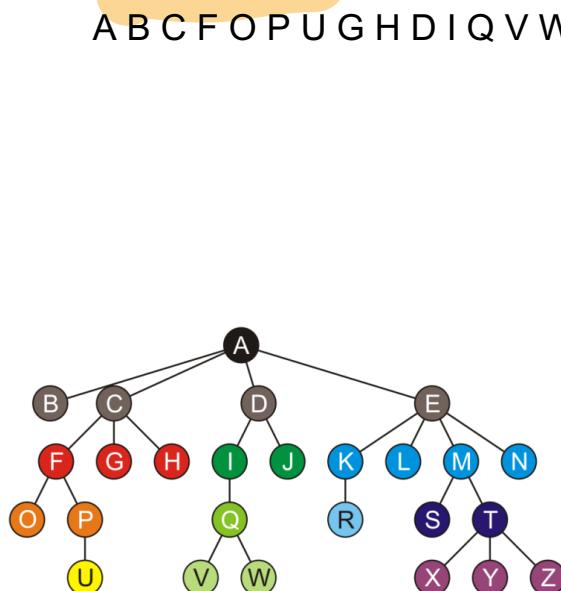
The transformation of a general tree into a left-child right-sibling binary tree has been called the Knuth transform

Order

Traversals

Root Left Right

A **pre-order** traversal of the original tree is identical to the **pre-order** traversal of the Knuth transform



Traversals

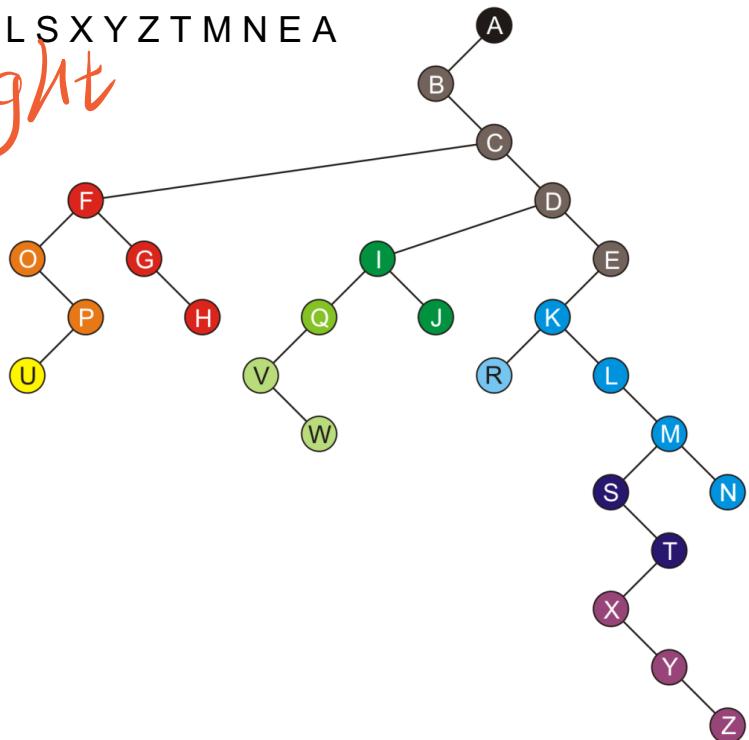
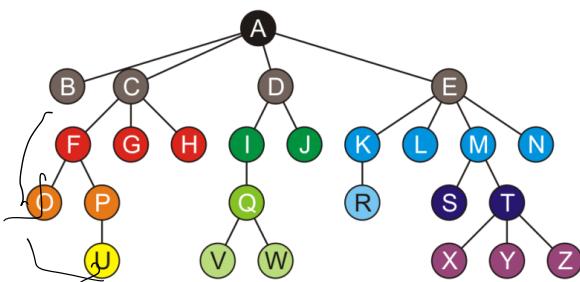
L Gt, R ght, Root



A **post-order** traversal of the original tree is identical to the **in-order** traversal of the Knuth transform

BOU PFG HCV WQIJDRKL SXYZ T MNE A

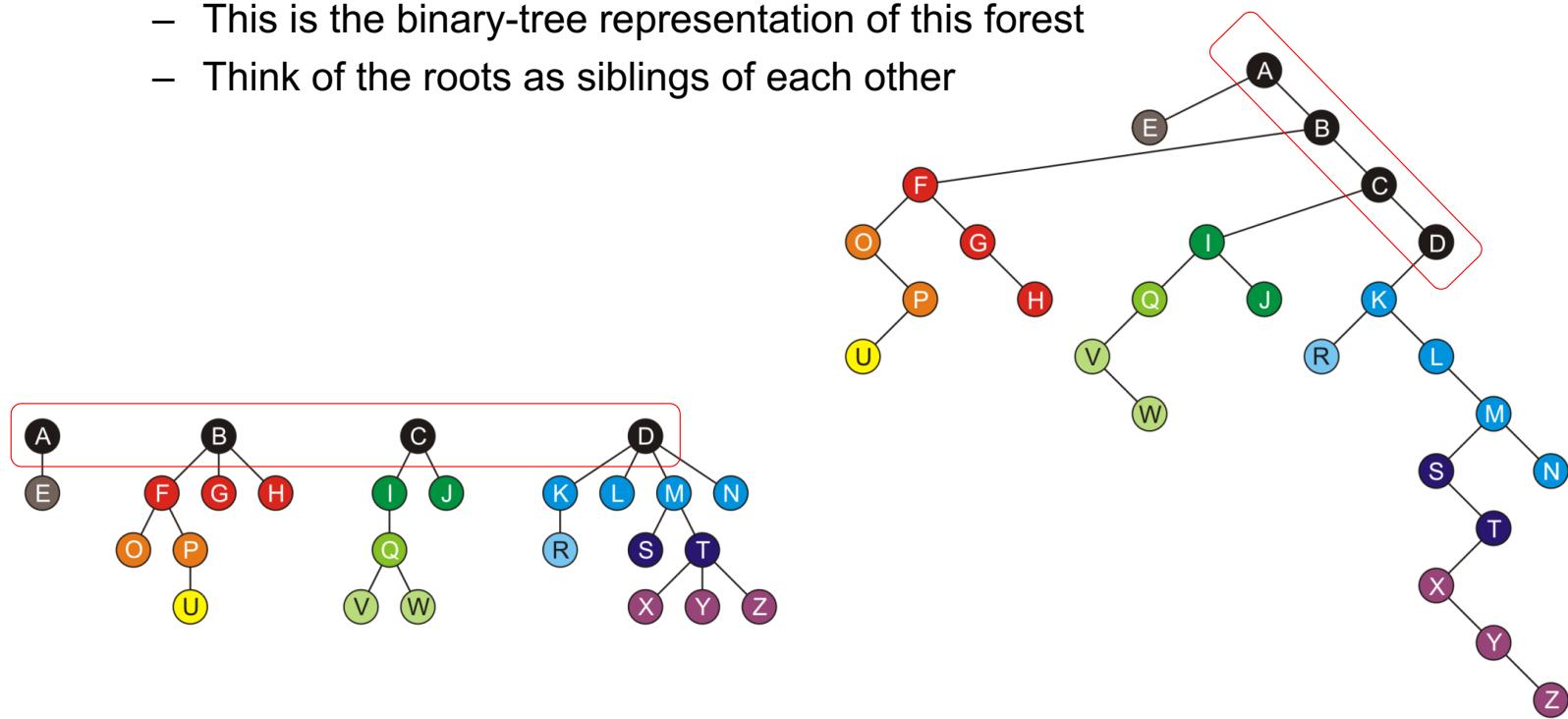
Left, Root, Right



Forests

A forest can be stored in this representation as follows:

- Choose one of the roots of the trees as the root of the binary tree
- Let each subsequent root of a tree be a right child of the previous root
- This is the binary-tree representation of this forest
- Think of the roots as siblings of each other



Implementation

The class is similar to that of a binary tree

```
template <typename Type>
class LCRS_tree {
    private:
        Type element;
        LCRS_tree *first_child_tree;
        LCRS_tree *next_sibling_tree;

    public:
        LCRS_tree();
        LCRS_tree *first_child();
        LCRS_tree *next_sibling();
        // ...
};
```

Implementation

The implementation of various functions now differs

```
template <typename Type>
int LCRS_tree<Type>::degree() const {
    int count = 0;

    for (
        LCRS_tree<Type> *ptr = first_child();
        ptr != nullptr;
        ptr = ptr->next_sibling()
    ) {
        ++count;
    }

    return count;
}
```

Implementation

The implementation of various functions now differs

```
template <typename Type>
bool LCRS_tree<Type>::is_leaf() const {
    return ( first_child() == nullptr );
}
```

Implementation

The implementation of various functions now differs

```
template <typename Type>
LCRS_tree<Type> *LCRS_tree<Type>::child( int n ) const {
    if ( n < 0 || n >= degree() ) {
        return nullptr;
    }

    LCRS_tree<Type> *ptr = first_child();

    for ( int i = 0; i < n; ++i ) {
        ptr = ptr->next_sibling();
    }

    return ptr;
}
```

Implementation

The implementation of various functions now differs

```
template <typename Type>
void LCRS_tree<Type>::append( Type const &obj ) {
    if ( first_child() == nullptr ) {
        first_child_tree = new LCRS_tree<Type>( obj );
    } else {
        LCRS_tree<Type> *ptr = first_child();

        while ( ptr->next_sibling() != nullptr ) {
            ptr = ptr->next_sibling();
        }

        ptr->next_sibling_tree = new LCRS_tree<Type>( obj );
    }
}
```

Implementation

The implementation of various functions now differs

- The size doesn't care that this is a general tree...

```
template <typename Type>
int LCRS_tree<Type>::size() const {
    return 1
        + ( first_child() == nullptr ? 0 : first_child()->size() )
        + ( next_sibling() == nullptr ? 0 : next_sibling()->size() );
}
```

Implementation

The implementation of various functions now differs

- The height member function is closer to the original implementation

```
template <typename Type>
int LCRS_tree<Type>::height() const {
    int h = 0;

    for (
        LCRS_tree<Type> *ptr = first_child();
        ptr != nullptr;
        ptr = ptr->next_sibling()
    ) {
        h = std::max( h, 1 + ptr->height() );
    }

    return h;
}
```

Summary

This topic has covered a binary representation of general trees

- The first child is the left sub-tree of a node
- Subsequent siblings of that child form a chain down the right sub-trees
- An empty left sub-tree indicates no children
- An empty right sub-tree indicates no other siblings

References

- [1] Cormen, Leiserson, Rivest and Stein, *Introduction to Algorithms*, 2nd Ed., MIT Press, 2001, §19.1, pp.457-9.
- [2] Weiss, *Data Structures and Algorithm Analysis in C++*, 3rd Ed., Addison Wesley, §6.8.1, p.240.

Summary

- Binary tree
 - Each node has two children
 - In-order traversal
- Perfect binary tree
 - Number of nodes, height, number of leaf nodes, average depth
- Complete binary tree
 - Height, array storage
- Left-child right-sibling binary tree