

Stacks

Example:- Glasses plates arranged in a drum which is hot & sterilized so that plates should be drawn from Top.

There is a spring which push a plate up when a plate is drawn

Applications

- ① Recursion
- ② Conversion of infix to postfix expression
- ③ Parsing Eg:- Matching paranthesis, tags, items
- ④ Browsing, Text editors (Back, Redo, Undo)
- ⑤ Evaluation of postfix expression
- ⑥ Tree traversals and Graph traversals

Implementation of Stack using Arrays

Disadvantage:- Predict the size of stack (array)

Advantage:- ① Faster ② 2

All operations take constant time (in case of Arrays & LL)

```
int stack[MAX];
```

```
int top = -1 // empty
```

```
void push (int item)
```

```
{
```

```
if (top == (MAX-1))
```

```
printf ("Overflow");
```

```
else {
```

```
top = top + 1;
```

```
stack[top] = item;
```

```
stack[++top] = item.
```

```
int pop ()
```

```
{ int temp;
```

```
if (top == -1)
```

```
printf ("Underflow");
```

```
return -1;
```

```

else {
    temp = stack[top];
    temp = stack[top--];
    top = top - 1;
}
return temp;
}

```

Note:- Here, if we delete an element, top is decremented.
 Later we push some element, we override the previous element
 Takes $O(1)$ time.

Linked list implementation of stack

Elements are created from heap memory dynamically

struct node

{

int i;

struct node *link;

};

push(int item)

{

// p → size

struct node *p = (struct node *) malloc (sizeof(struct node));

if (p == NULL)

{

printf("Malloc error");

return;

}

p → data = item

p → link = NULL;

p → link = head;

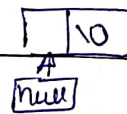
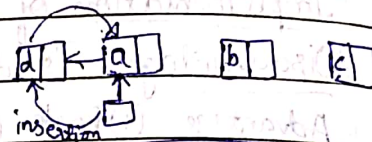
head = p

}

int pop()

{

int item; struct node *p;



// new created node linked to old head
 // old head is updated to new head


```
if (head == NULL)
```

```
printf("Underflow");
```

```
return -1;
```

```
}
```

```
item = head->i;
```

```
p = head;
```

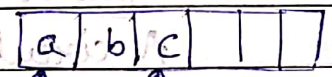
```
head = head->next;
```

```
free(p);
```

```
}
```

Implementation of a Queue using Circular array

A Queue is a empty hollow cylinder. Both its ends are open
we shall put watermelons into it.



It will drop due to gravitational force

Front → Return first element in the queue (~~last element~~)

Rear → Return last element in the queue

Deletion is done from front so that the insertion order of
Insertion is done from rear queue is maintained

```
de));
```

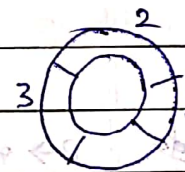
```
enqueue(item)
```

```
{
```

```
rear = (rear + 1) mod n;
```

```
if (front == rear)
```

```
{
```



// Rear & front points to 0
it is overflow

```
printf("Q is full");
```

```
if (rear == 0)
```

```
rear = n - 1;
```

```
else
```

```
rear = rear - 1;
```

```
return;
```

```
}
```

```
else { q[rear] = item;
```

```
return;
```

```
int Dequeue()
```

```
{ if (front == rear)
```

```
printf("Q is empty");
```

```
return -1;
```

```
} else
```

```
front = (front + 1) mod n;
```

```
item = q[front];
```

```
return item;
```


GATE 2012

Suppose a circular queue of capacity $(n-1)$ elements is implemented with an array of n elements. Assume that the insertion and deletion operations are carried out as using 'REAR' and 'FRONT' as array index variables respectively. Initially, $REAR = FRONT = 0$. The conditions $REAR = FRONT = 0$. The conditions to detect queue full and queue empty are:

Sol:- Queue Full

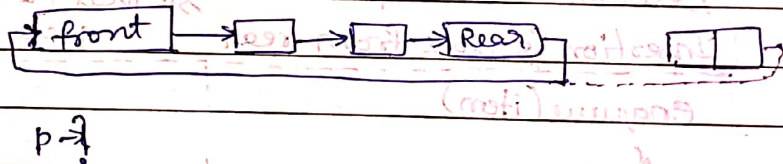
$$(rear + 1) \bmod n == front$$

Queue Empty

$$rear == full$$

Gate 2004

A circularly linked list is used to represent a Queue. A single variable 'p' is used to access the queue. To which node should p point such that both the operations enqueue and dequeue can be performed in constant time?



Sol:-

$$p \rightarrow rear$$

Gate 1994

Which of the following permutations can be obtained in the output (in the same order) using a stack assuming the input is in that order 1, 2, 3, 4, 5 in that order?

- a) 3, 4, 5, 1, 2 b) 3, 4, 5, 2, 1 c) 1, 5, 2, 3, 4 d) 5, 4, 3, 1, 2

Check

for a)

5
4
3
2
1

3 4 5 2 1

(b) is

5
4
3
2
1

5
4
3
2
1

1, 5, 4, 3, 2

5
4
3
2
1

5, 4, 3, 1, 2

Gate 1997

A priority queue 'Q' is used to implement a stack 'S' that stores characters. PUSH(c) is implemented as Insert(Q, c, k) where k is appropriate integer key chosen by implementation as DEletemin(Q). For a sequence of push operations, the keys chosen are in

- a) non-increasing order // decreasing order
- b) non-decreasing order
- c) strictly increasing order
- d) strictly decreasing order

Gate 2003

Let 'S' be stack of size $N \geq 1$ starting with the empty stack. Suppose we push first 'n' natural numbers in sequence, and then n pop operations. Assume that push & pop operations take X seconds each, and Y seconds elapse between the end of one such stack operation and the start of the next operation. For $m \geq 1$, define the stack life of m is the time elapsed from the end of push(m) to the start of the pop operation that removes m from S. The average stack-life of an element of this stack is

3	Push or Pop: X
2	Blw 2op: Y
1	

$$\text{One element: } X + \text{Stack life} - \text{Pop} = X + Y - X = Y$$

$$\text{Two element: } 2X + 2Y - 2X = 2(X + Y) - X$$

$$n \text{ element: } nX + nY - nX = n(X + Y) - X$$

Gate 2006

An implementation of a queue, using two stacks S1 & S2, is given below


```
void insert(a, x)
```

Q. $push(s1, x)$

```
void delete(Q, x)
```

3

if (stack_empty(s2)) then

if (stack.empty(s1)) then

१

```
print("Q is empty");
```

return;

۳

```
else while (!stock.empty(s1))
```

3

$$x = \text{pop}(s1);$$

push(s2, x):

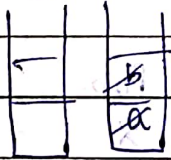
۲

$$\dot{x} = \text{pop}(32)$$

3.

Let n insert & m ($\leq n$) delete operations be performed in arbitrary order on an empty queue Q . Let x & y be the numbers of push and pop operations performed respectively in the process. Which one is true for all m & n ?

sd



Nelements

2 push 2 pop. Ans :- $m+n \leq x \leq 2n$

2m. $\leq y \leq m+n$

1 bob Push
1 bob Best case: $2m + (n-m) = m+n$

(2c) ← Worst Case: In ~~the~~ Insertion of

Pop:- Best Case = $2m$ // Remove first ele

Worst case = $2n + (m - n)$

$\frac{1}{2} = \frac{1}{2}$

$$m+n \leq x \leq 2n$$
$$2m \leq y \leq 2m+n$$

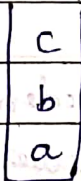
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other &
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new

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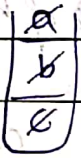
GATE-2000 $\leftrightarrow$ GATE 2014

- (1) Suppose a stack implementation supports, in addition to PUSH, and POP, an operation "reverse" the order of elements on the stack.
- (2) Implement a queue using the above stack implementation. Show how to implement "ENQUEUE" using ~~1-3~~ ¹⁻³ ~~single~~ ^{three} operation and "DEQUEUE" using a sequence of ~~3~~ ³ operations.

Sol:-

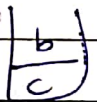
a b c
↑ ↑ ↑

Reverse

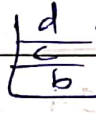


a b c

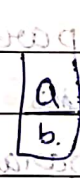
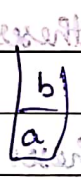
After popping a, if we want to insert then reverse

Reverse $\Rightarrow$ 

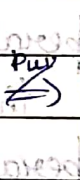
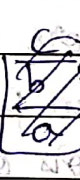
Insert

Enqueue $\rightarrow$ Reverse Stack $\rightarrow$ 3 operation

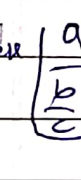
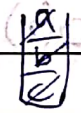
Reverse



Reverse



Reverse

Dequeue $\rightarrow$ 1 operation

a b c

all ele
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insert
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ick &
more
n

Applications of Stacks

SURYA Gold

Date _____ Page _____

1) Conversion of infix expression to postfix expression

Eg:-

(4) $a * b + c$ ① $a + b * c$ ② $a + b - c$ ③ $a + (b - c)$

$ab * + c$ $a + bc *$ $ab + - c$ $a + bc -$

$ab * c +$ $abc * +$ $ab + c -$ $abc - +$

Using Stack

Note:-

① $a + b * c$
↑ ↑ ↑ ↑ ↑

An operator of high precedence can sit on operator of lower precedence

Stack:-
| + | * |
a b c

But an operator of lower precedence can not sit on operator of higher precedence

② $a * b + c$
↑ ↑

③ $a * b + (c - d)$
↑

$a * b + (c - d)$

| * | + |

| * | + | (| - |) |

$a * b + cd -$

$a b * c +$

$ab * cd - +$

$ab * + cd -$

$ab * cd - +$

$+ < ($

$(< +$

Note:- Operators within parentheses has higher precedence than parentheses

• Operators outside parentheses has lower precedence than parentheses

Space complexity = $O(n)$

Algorithm

① Create a stack

② For each character 't' in the input

if ('t' is an operand)

output 't' ;

else if ('t' is a right parenthesis)

pop and output tokens until a left parenthesis is popped (but don't output)

else // t is an operator or left parenthesis

{
pop and output tokens until one of lower priority than 't' is encountered or a left parenthesis is encountered or stack is empty.

Push t
}

Time complexity :- $O(n)$

Uses operator stack

2) Postfix evaluation algorithm

Time complexity :- $O(n)$, Uses operand stack

Eg: ① $3 * 2 + 1$ ② $3 + 2 * 1$

$6 + 1$

$5 * 1$

Postfix :-

$3 + 2$

$3 2 +$

First operand becomes
Second operand
and
vice versa

$3 2 + 1 *$

// Push result to stack

$3 + 2$

5

Space complexity :- $O(n)$

Algorithm

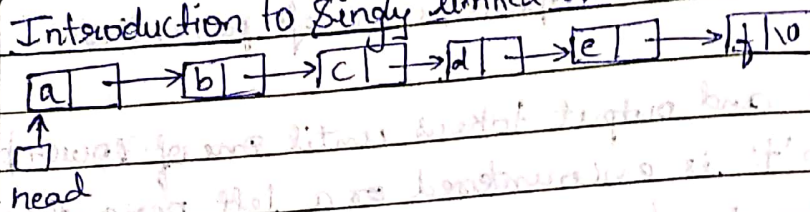
- ① Scan the postfix string from left to right
- ② Initialize an empty stack
- ③ Repeat steps 4 & 5 until all the characters are scanned
- ④ If the scanned character is an operand, push it onto stack
- ⑤ If the scanned character is an operator, & if operator is unary, then pop an element from the stack. If the operator is binary, then pop two elements from the stack. After popping the elements, apply the operator to those popped elements. Push result onto the stack
- ⑥ After all the elements are scanned, the result will be in the stack

Linked List

SURYA Gold

Date _____ Page _____

Introduction to Singly linked list



Struct node

{

char data;

struct node *link;

};

struct node *p; ~~struct node *head;~~

p = head -> link -> link;

p -> link -> link -> link = p;

head -> link = p -> link;

printf("%c", head -> link -> link -> link -> link -> data);

%p;

Advantage:-

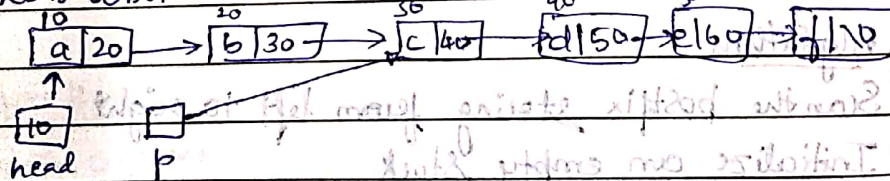
1> Sequential access of element. Takes $O(n)$ time

In arrays, it takes $O(1)$ time

2> Searching, takes $O(n)$ time if elements are unordered

Ans for Q

Let's assume



p = head -> link -> link

20 -> link

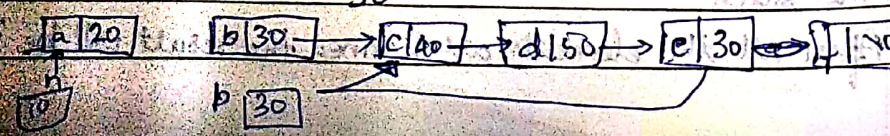
p = 30

p -> link -> link -> link = p

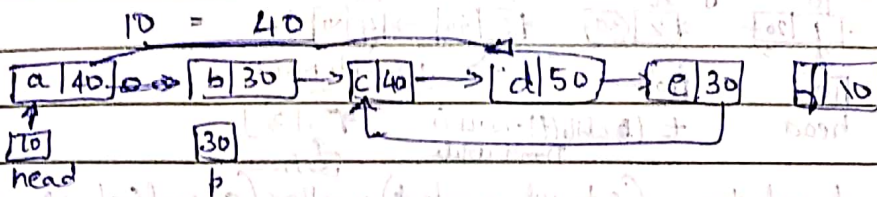
30 -> link -> link

40 -> link -> link = 50 -> link

50 -> link = 60 = p



head → link = p → link;



print head → link → link → link → link → data

40 → link → link → link → data

50 → link → link → data

30 → link → data

40 → data

d → data

Traversing a singly linked list

On a list, we can perform

i) Traversing

ii) Inserting

iii) Deleting

struct node

{

int i;

struct node *link;



head

Moving head may cause loss of nodes created dynamically
(since it does not have any name)

struct node *t;

t = head

while (t != NULL) {

printf("%d", t → data);

printf("%d", t → i);

t = t → link;

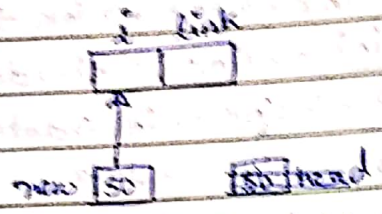
while (t != NULL) {

while (t != NULL) {

Inserting an element in SLL



struct node *new = (struct node *) malloc(sizeof(struct node))



head = new // Don't do this info is lost

At beginning: new → link = head
head = new

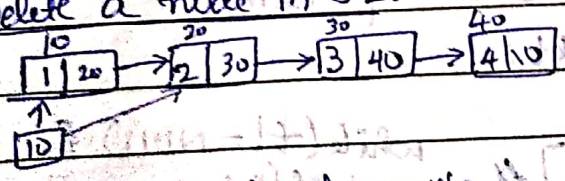
At end: struct node *t; t = head
while (t != NULL) // Don't write
t = t → next
while (t → next != NULL) // Don't write
t = t → next
t → next = new
new → next = NULL

After node:
which we want
Eg: after 2nd node

struct node *t = head	
while (t → i != 2)	X
t = t → next	
t → next = new	
new → next	

new → link = t → link
t → link = new

Delete a node in SLL



At beginning:

struct node *t = head; head = head → next
free(t)
if (head == NULL) return;
if (head → next == NULL) (not = t) link
free(head)
head = NULL;

From:
tail

```

struct node *t = head
while (t->next != NULL)
    t = t->next
free(t->next)
t->next = NULL

```

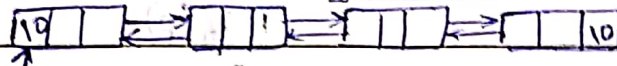
Apachub
nath
Eg: 3

```

struct node *t = head
while (t->next->i != 3)
    t = t->next;
struct node *t1 = t->next
t->next = t->next->next
free(t1)

```

Insertion into doubly linked list



head



t

```

struct node
{
    int i;

```

```

    struct node *prev;

```

```

    struct node *next;
}

```

At
Beginning:

```

t->next = head
head = t
t->prev = NULL
t->prev head->next->prev = head;

```

At
end:

```

while (p->next != NULL)
    p = p->next
p->next = t
t->prev = p
t->next = NULL;

```

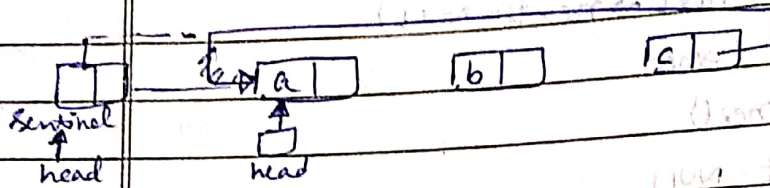
After
Node:

Eg:

```

t->prev = p;
t->next = p->next;
p->next = t
t->next->prev = t

```


Circular linked list

$b = \text{head}$

while ($b \rightarrow \text{next} \neq \text{head}$)

Sentinel is a special node that contains count of nodes pointed by head

Printing the elements of SLL using recursion

Program 1:-

```
void f(struct node *p)
{
```

```
1 if(p)
```

```
2 {
```

```
3 printf("%d", p->data);
```

```
4 f(p->link);
```

```
5 }
```

```
}
```

Program 2:-

```
void f(struct node *p)
```

```
{
```

```
1 if(p)
```

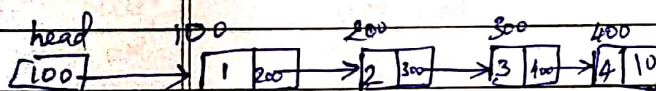
```
2 {
```

```
3 printf("%d", p->data);
```

```
4 f(p->link);
```

```
5 }
```

```
}
```



$b \rightarrow f() \rightarrow 100$

popped off

$b \rightarrow f() \rightarrow 400$

$P \rightarrow f() \rightarrow 300$

$P \rightarrow f() \rightarrow 200$

$b \rightarrow f() \rightarrow 100$

main()

%p: 1 2 3 4

%p: 4 3 2 1

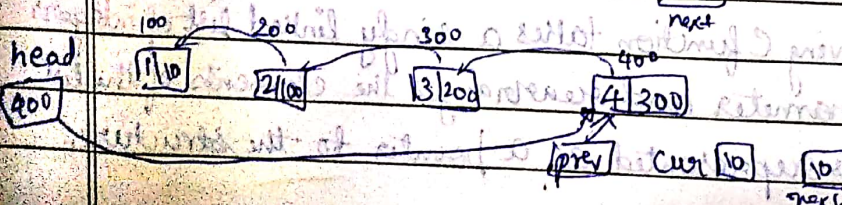
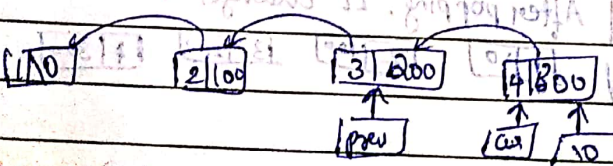
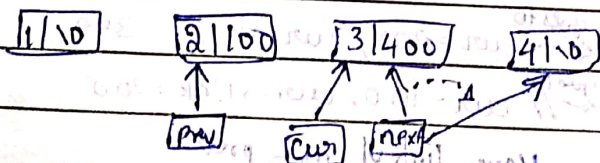
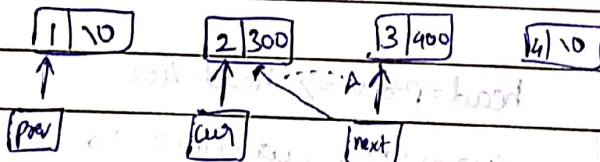
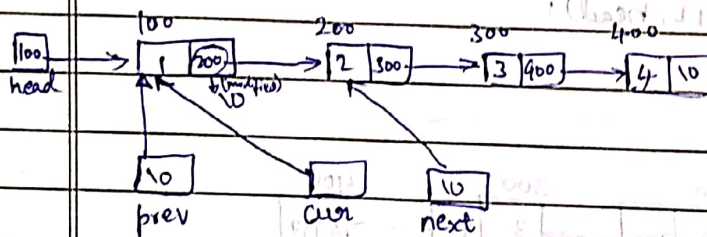
Reversing an SLL using iterative program

struct node


```

int *reverse(struct node **head)
{
    struct node *prev = NULL, *nextNode = NULL;
    while (*head)
    {
        nextNode = (*head) -> next;
        (*head) -> next = prev;
        prev = (*head);
        (*head) = nextNode;
    }
    return prev;
}

```



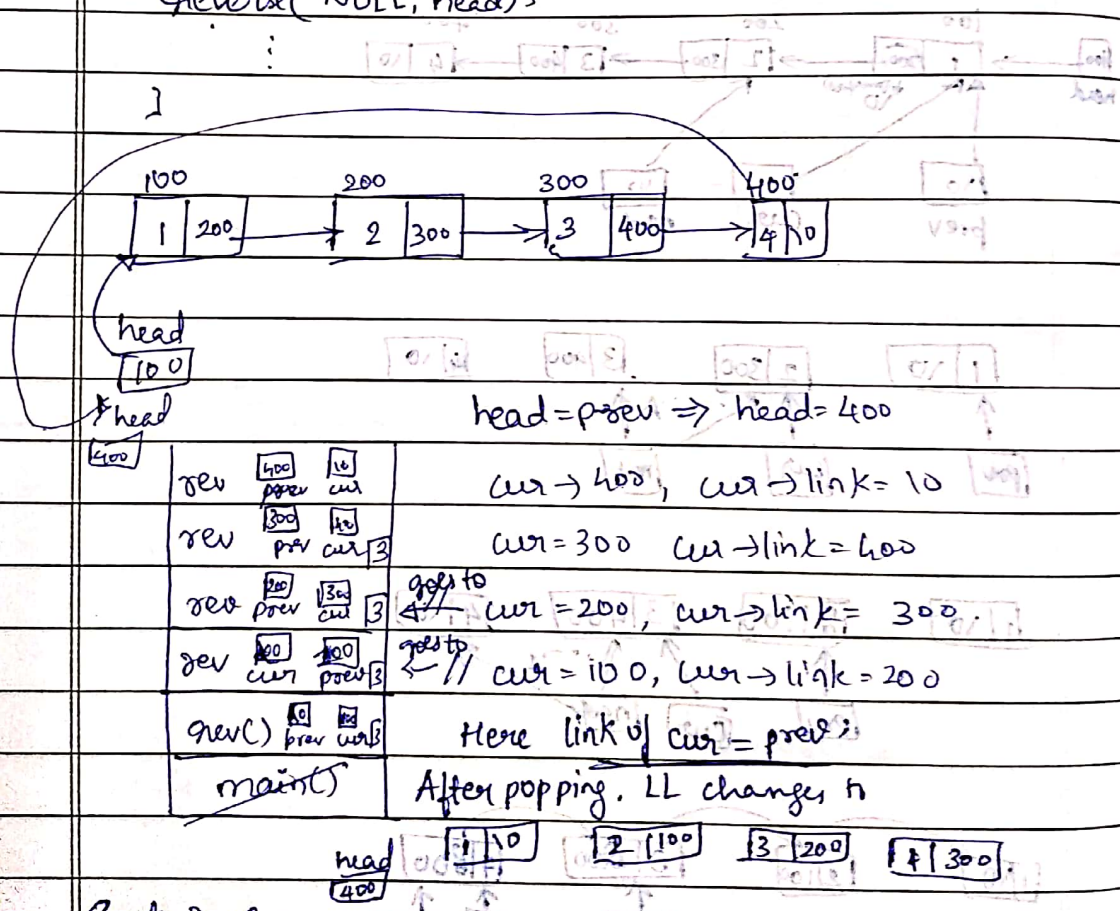
Recursive program for reversing an SL

```

struct node *head;
void reverse(struct node *prev, struct node *cur)
{
    1 if(cur)
    {
        2 reverse(cur, cur->link);
        3 cur->link = prev;
        4 }
    else
        head = prev;
}

void main() {
    :
    reverse(NULL, head);
    :
}

```



Gate 2008

The following C function takes a singly linked list of integers as a parameter and rearranges the elements of the list. The list is represented as a pointer to the structure.

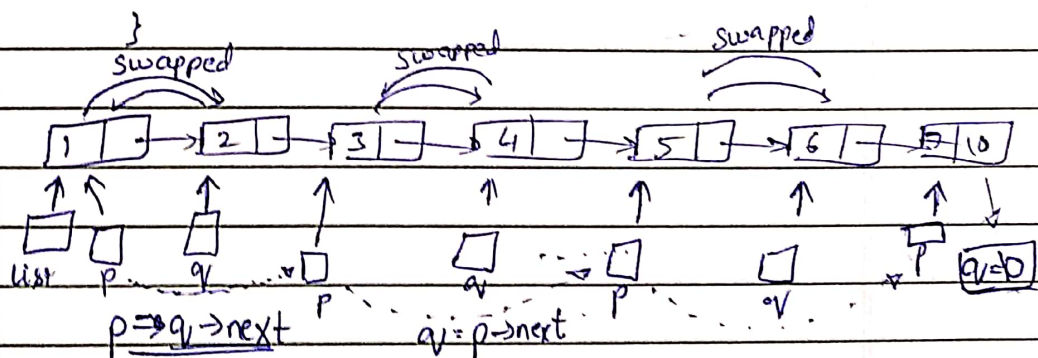
The function is called with the list containing the integers 1, 2, 3, 4, 5, 6, 7 in given order. What will be the contents of the list after the function completes execution

```

struct node {
    int val;
    struct node *next;
};

void rearrange(struct node *list)
{
    struct node *p, *q;
    int temp;
    if (!list || !list->next) return;
    p = list;
    q = list->next;
    while (q)
    {
        temp = p->val;
        p->val = q->val;
        q->val = temp;
        p = q->next;
        q = p ? p->next : 0;
    }
}

```

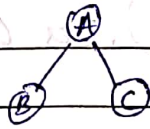


o/p: 2 1 4 3 6 5 7

GATE 2010
The follow

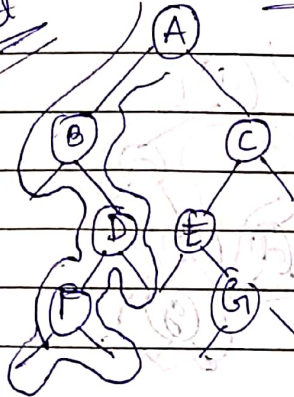
Introduction to tree traversals

- 1) Inorder traversal - Left Root Right - ~~A~~ BAC
- 2) Preorder traversal - Root Left Right - ABC
- 3) Postorder traversal - Left Right Root - BCA



Put dummy nodes (links)

Shortcut



Pre - ABDFCEG - Ist visit

In - BFDAEGC - IInd

Post - FDBGEC A - IIIrd

Implementation of traversals and time and space analysis

struct node

{

int data;

struct node *left, *right;

}

void Inorder(struct node *t)

{

if (t != NULL) { ~~or~~ if (t)

1 Inorder(t->left);

2 printf("%d", t->data);

3 Inorder(t->right);

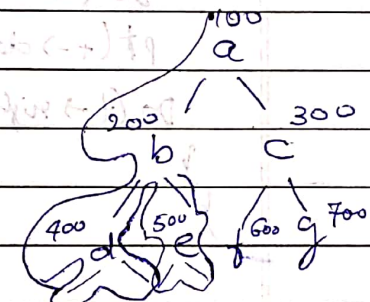
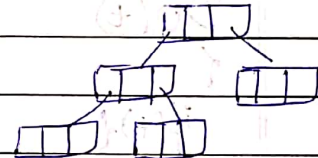
}

}

prints node during second visit

o/p: 400 200 500

d b e a b.



t=500 10	t=10
t=10	t=10
t=400 2	t=100 2
t=200 1 2	t=10
Inorder t=100	t=10
main()	t=500 2

no visiting node takes constant time

Every node visited 3 times

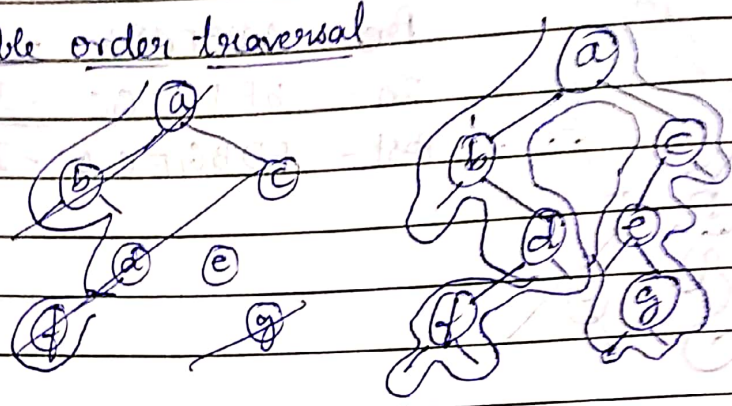
Time complexity: $O(n)$

Space complexity: Depends on levels of tree

n nodes $\rightarrow n$ levels

All nodes in one stream (all left), This called Queue tree $O(n)$

Double order traversal



b f d a e c g c

DO(t)

{

if(t) {

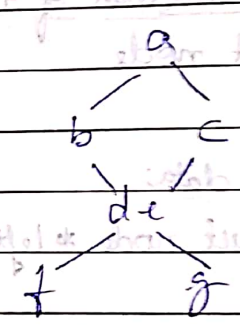
pf(1, t -> data);

DO(t -> left);

pf(t -> data);

DO(t -> right);

}



a b d f f d a c e g g c

Triple Order Traversal

TO(t)

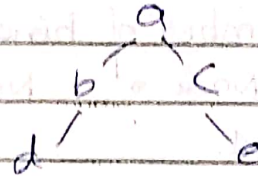
{

if(t) {


```

{
    pf("%d", t->data);
    TD(t->LC);
    pf("%d", t->data);
    TD(t->RC);
    pf("%d", t->data);
}

```



a b d d d b b a c c e e e c a

✓ Indirect recursion on trees

```
void A(struct node *t)
```

```
{
```

```
    if(t)
```

```
    {
```

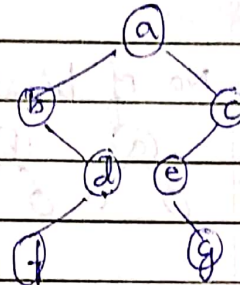
```
        1. printf("%d", t->data);
```

```
        2. B(t->left)
```

```
        3. B(t->right)
```

```
    }
```

```
}
```



```
void B(struct node *t)
```

```
{
```

```
    if(t)
```

```
    {
```

```
        1. printf("%d", A(t->left));
```

```
        2. printf("%d", t->data);
```

```
        3. A(t->right);
```

```
    }
```

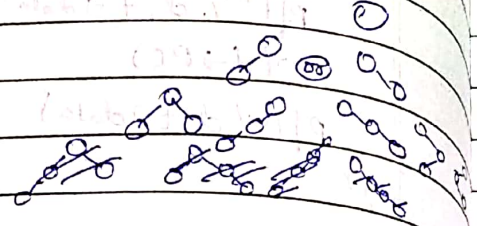
```
}
```

Skewed binary tree is tree which has only one type of subtrees. If a tree has only left subtrees then it is left skewed tree & vice versa.

Number of binary trees possible

At Node • No. of binary trees possible

1	1
2	2
3	3
4	4



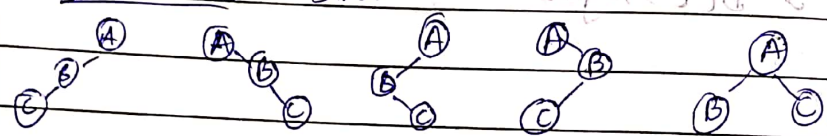
No. of binary trees for n nodes (for unlabeled nodes)

$$\text{3 nodes} = \frac{2n C_n}{n+1} = \frac{2 \times 3 C_3}{4} = \frac{6 C_3}{4} = 5$$

No. of binary trees for n nodes (for labelled nodes)

$$= \frac{2n C_n}{(n+1)n!} = \frac{6 C_3}{4 \times 3 \times 2 \times 1} = \frac{6!}{3!3!} = \frac{6 \times 5 \times 4}{3 \times 2 \times 1} \times 1 = 5$$

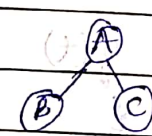
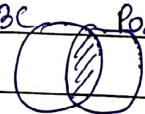
Preorder ABC - 5 trees



Preorder ABC & Postorder CBA

Inorder - BAC Preorder - ABC

Preorder ABC Postorder CBA



Inorder BCA & Postorder CBA

n nodes, Preorder $\rightarrow \frac{2n C_n}{n+1}$

Binary trees

Preorder & Postorder - No unique BT or more than 1

Inorder, Postorder, Preorder - Unique BT exactly one

Construction of unique binary tree

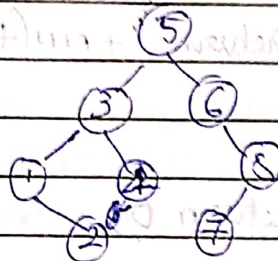
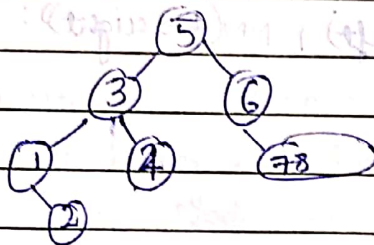
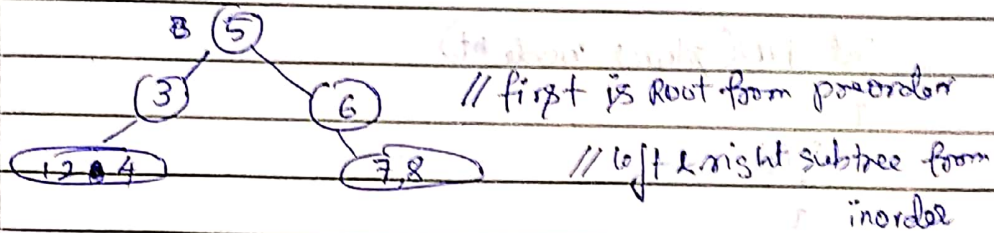
Inorder: 1, 2, 3, 4, 5, 6, 7, 8

①

Preforder: 5, 3, 1, 2, 4, 6, 8, 7

Postorder = ?

Inorder: -

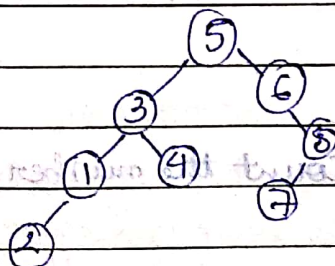
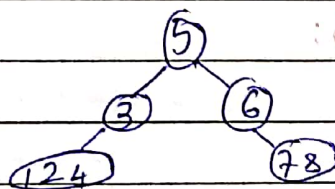


Postorder: 2 1 4 3 7 8 6 5

// 3rd time

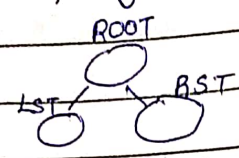
② Inorder: 1, 2, 3, 4, 5, 6, 7, 8

Postorder: 2 1 4 3 7 8 6 5



7min watched

Recursive program to count the number of nodes



$$NN(T) = 1 + NN(LST) + NN(BST)$$

$$= 0; \text{ if } T \text{ is null}$$

```

int NN(struct tnode *t)
{
    if(t)
    {
        return (1 + NN(t->left) + NN(t->right));
    }
    else
    {
        return 0;
    }
}
  
```

OR

```

int NN(struct tnode *t)
{
    if(t)
    {
        int l, r;
        l = NN(t->left);
        r = NN(t->right);
        return (1 + l + r);
    }
    else
    {
        return 0;
    }
}
  
```

5min watched

Recursive program to count the number of leaves and non leaves

$$NL(T) = 1; \text{ Tree is a leaf}$$

$$= \frac{NL}{2}(LST) + NL(RST)$$

NL(struct node *t)

{

if (t == NULL)

return 0;

if (t->left == NULL && t->right == NULL)

return 1;

else

return (NL(t->left) + NL(t->right));

}

Recursive program to find the full nodes

Node having 2 children - Full node

Full Node is a subset of Non leaf

Not every non leaf is a full node

FN(T) = 0, T = NULL

0 if T = leaf

= FN(T->LST) + FN(T->RST), T has 1 child

= FN(T->LST) + FN(T->RST) + 1

int FN(struct node *t)

{

if (!t) return 0;

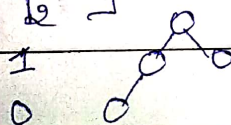
if (!t->left && !t->right)

return 0;

if return FN(t->left + t->right) + (t->left && t->right ? 1 : 0);

Recursive program to find the height of a tree

Height of any node, to leaf its distance



$H(T) = 0$ if T is null
 0 if T is a leaf
 $1 + \max(H(LST), H(RST))$

int H(struct node *t)

{

if(!t) return 0;

if(!t->right & !t->left) return 0;

~~return(1 + H(t->left) > H(t->right))~~

int l, r;

l = H(t->left)

r = H(t->right)

//return (1 + max(l, r));

return(1 + (l > r) ? l : r);

GATEFORUM

Binary Search Trees

Properties:-

A binary tree T has n leaf nodes. The no. of nodes

- ① A tree with n nodes has exactly $n-1$ edges ✓
- ② In a tree, every node except root has exactly one parent.
- ③ Maximum no. of nodes in a binary tree of height k :
 $2^{k+1} - 1, k \geq 0$
- ④ Consider a nonempty binary tree with n_i nodes in number of nodes with i children ($i=0,1,2$) then, $n_2 = n_0 - 1$
- ⑤ Maximum no. of nodes in a binary tree at level i is $2^i, i \geq 0$
- ⑥ Maximum depth of a binary tree with n nodes is n
- ⑦ The minimum height of a binary tree with n nodes is $\log_2 n$
- ⑧ Maximum no. of leaves in a binary tree of height h / level 2^h or 2^l

GATE 2005

- (1) How many distinct binary search trees can be created out of 4 distinct keys

$$n = 4$$

$$B_n = \frac{1}{n+1} \binom{2n}{n} = \frac{2^n C_n}{n+1}$$

$$= \frac{1}{4+1} \times \frac{8!}{4!4!}$$

$$= \frac{1}{5} \times \frac{8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1}{4 \times 3 \times 2 \times 1 \times 4 \times 3 \times 2 \times 1}$$

$$= 14$$

$$\frac{1}{4} \times \frac{6!}{3!3!}$$

$$\frac{1}{4} \times \frac{6 \times 5 \times 4 \times 3 \times 2 \times 1}{3 \times 2 \times 1 \times 3 \times 2 \times 1} = 5$$

GATEFORUM

- (10) If a binary tree T has n leaf nodes, the number of nodes of degree 2 in T is $n-1$

- (11) No. of nodes a complete binary of depth d has $2^{d+1} - 1$

- (12) A complete binary tree with n non leaf nodes contain $2n+1$ nodes

- (13) The depth of a complete binary tree with n nodes is $\log_2(n+1) - 1$

- (14) The depth of a complete ternary tree with n nodes is $\log_3(2n+1) - 1$

- (15) The average total path length of a randomly built binary search tree with n nodes is $O(\log_2 n)$

- (16) Let i be the internal path length. Average number of comparisons needed for successful search in a binary tree of n nodes $(i+n)/n$

- (17) If m pointer fields are set aside in each node of a general tree to a point to a max no. of m children and if the number of internal nodes in the tree is n, then number of leaves is $n(m-1)+1$

- (18) No. of different binary trees with n nodes = $\frac{1}{n+1} \binom{2n}{n}$

- (19) There are $2^n - 1$ nodes in a full binary tree

- (20) For a binary tree, maximum no. of nodes at level height are $2^{h+1} - 1$ nodes

(21) Total number of external nodes in a binary tree are internal nodes + 1

$$e = i + 1$$

(22) The average total path length of a randomly built binary search trees with n nodes is $O(\log_2 n)$

(23) Time complexity of building a max-heap of n elements is $O(n)$

(24) Heap sort $\rightarrow O(n \log n)$

(25) Height of heap $\rightarrow O(\log n)$

(26) In heap property,

$$\text{function PARENT}(i) \rightarrow \lfloor i/2 \rfloor$$

$$\text{LEFT}(i) \rightarrow 2i$$

$$\text{RIGHT}(i) \rightarrow 2i + 1$$

(27) Number of comparisons in searching an element in BST is $O(n)$

(28) In a complete binary tree of n nodes, the maximum distance between 2 nodes is $2 \log_2 n$

Max heap, insert & deletion $\sim O(\log n)$

(1) In a run of quicksort of 100 items, the main loop of quicksort has already completed 32 iterations. How many elements are guaranteed to be in final spot?

Sl:- 32

(2) In a selection sort of n elements, $n-1$ the swap function called in the complete execution of an algorithm

(3) Given ' n ' k -digit numbers where each digit can take up d values. Running time of radix sort is $O(k(n+d))$

(4) Using universal hashing and collision resolution by chaining in an initially empty hash table with m slots, the expected time to handle n insertion operations is $\Theta(n)$

- (5) Given an open-address hash table with a table of m slots and n elements present, the expected number of probes for a successful search of a key is $\frac{m}{n} [\log_2 m - \log_2 (m-n)]$
- (6) $O(1)$, $O(m^2)$ probe sequences are used in quadratic probing & double hashing
- (7) $|V|-1$ iterations of relaxing the entire set of edges are performed in Bellman-Ford algorithm
- (8) Height of decision tree on n elements $\log_2(n!)$
- (9) $2n-1$ comparisons are required for merging 2 sorted lists of n element
- (10) Running time of an efficient algorithm to find an Euler tour in a graph is $O(|E|)$
- (11) Running time of the fastest algorithm to calculate the shortest path between any 2 vertices of a graph where all edges have equal weight $O(E+V)$
- (12) $\frac{n(n-1)}{2}$ no. of swaps required in an algorithm to calculate the transpose of a directed graph represented as adjacency matrix
- (13) Running time of an efficient algorithm to compute the square of a directed graph represented as adjacency matrix $O(V^3)$
- (14) Running time of an efficient algorithm to find all cut vertices of a graph $O(|E|)$

(15) Let H be a finite collection of hash functions that map a universe U of keys into $\{0, 1, \dots, m-1\}$. H is said to be universal if for each pair of distinct keys $k \neq l \in U$ the no. of hash functions $h \in H$ for which $h(k) = h(l)$ is at most $|H|/m$.

Note:-

In Preorder, Root is first element
In Postorder, Root is last element

Steps:-

- (1) Find the root.
- (2) Find left & right subtrees w.r.t root found
- (3) Find the root in corresponding LST & RST
- (4) Repeat step 2 and 3 until empty

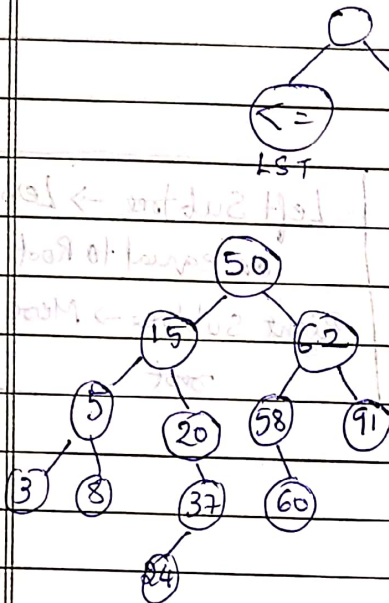
Binary Search Trees

It is a special kind of binary which are helpful in searching of elements

GATE 96

50, 15, 62, 5, 20, 58, 91, 3, 8, 37, 60, 24

Nodes are not ~~has~~ repeated. Used to store heap. Points to records.

GATE 2005

Postorder: 10, 9, 23, 22, 27, 25, 15, 50, 95, 60, 40, 29

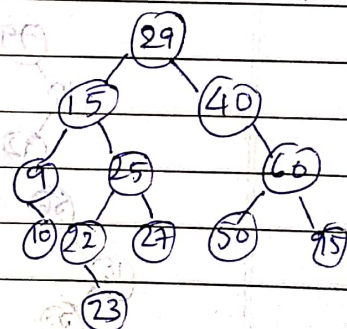
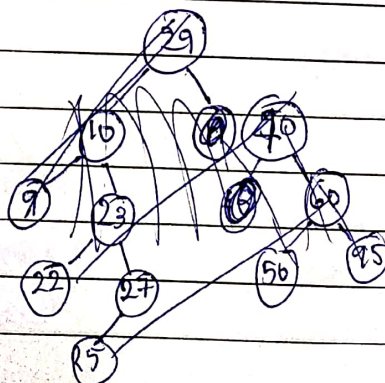
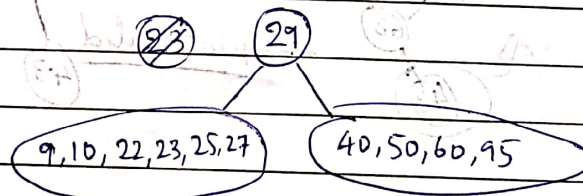
Inorder: Sorted order $\rightarrow$ 9, 10, 15, 22, 23, 25, 27, 29, 40, 50, 60, 95

Preorder: -

Preorder: 29, 15, 9

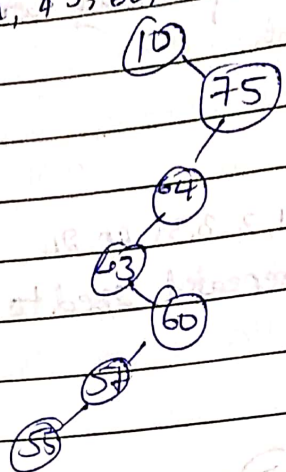
10, 25, 22, 23, 27,

40, 60, 50, 95

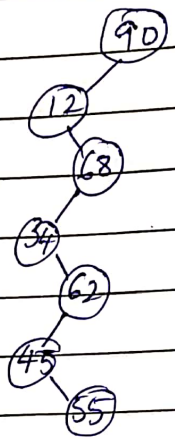


GATE 2006 → 55 search

a) 10, 75, 64, 43, 60, 57, 55

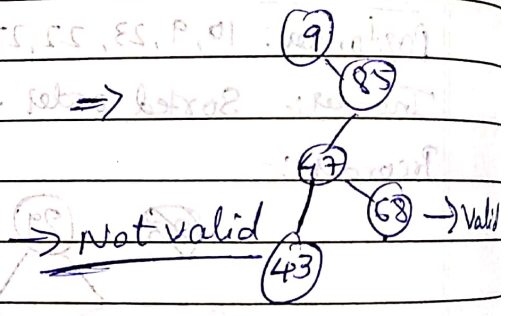
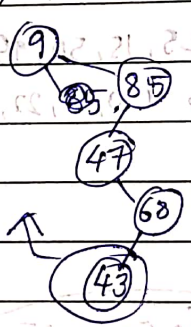


b) 90, 12, 68, 34, 62, 45, 55



Left Subtree → Less than
or equal to Root
Right Subtree → More than
root

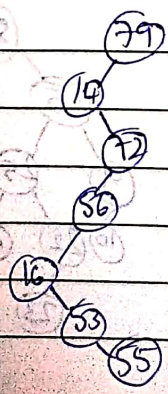
c) 9, 85, 47, 68, 43, 57, 55



Not valid

Valid

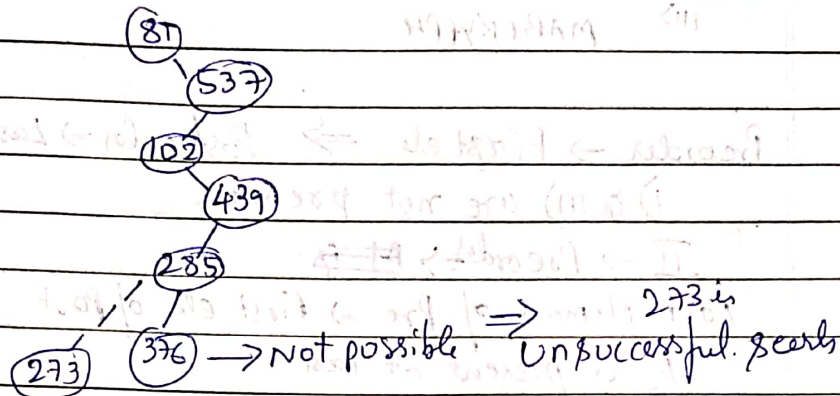
d) 79, 14, 72, 56, 16, 53, 55



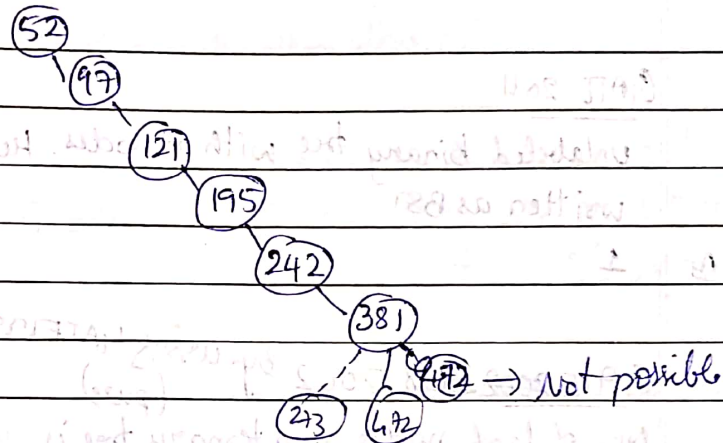
GATE 2008

273 is unsuccessful search

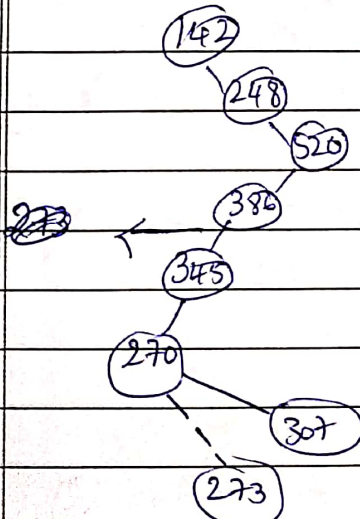
a) 81, 537, 102, 439, 285, 376, 305



b) 52, 97, 121, 195, 242, 381, 472

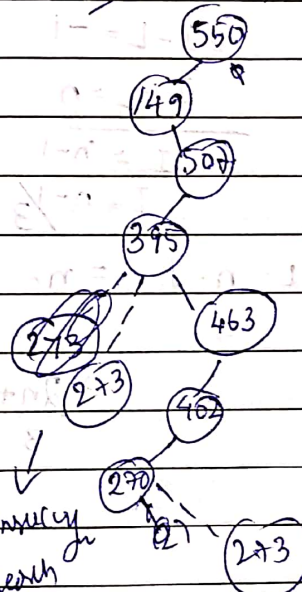


c) 142, 248, 520, 386, 345, 270, 307



⇒ Successful search

d) 550, 149, 507, 395, 463, 402, 270



Unsuccessful search

GATE - 2008

(1)

i) M B C A E H P Y K

ii) K A M B Y P F H

iii) M A B C K Y F P H

Preorder $\rightarrow$ First ele $\Rightarrow$ Post order $\Rightarrow$ Last ele

i) & ii) are not preorder

ii $\rightarrow$ Preorder $\Rightarrow$ ~~M~~ is

Last element of Pre $\rightarrow$ First ele of Post

K is present at last

i $\rightarrow$ Postorder

iii $\rightarrow$ Inorder

GATE 2011

unlabeled binary tree with n nodes. How it can be written as BST.

Ans

1

GATE 2002 1998 2002 by using GATE 1998 formula (pure) IT 2005

No. of leaf nodes in a ternary tree is

$$L = I(3-1) + 1$$

$$L + I = n$$

$$2I - L = -1$$

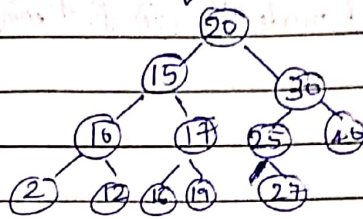
$$I + L = n$$

$$3I = n - 1$$

$$I = \frac{n-1}{3}$$

$$L = n - I = n - \frac{n-1}{3}$$

$$= \frac{2n+1}{3}$$

Delete a Node from BSI

3 types of deletion

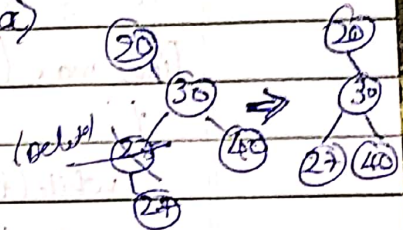
① Leaf

② Non Leaf

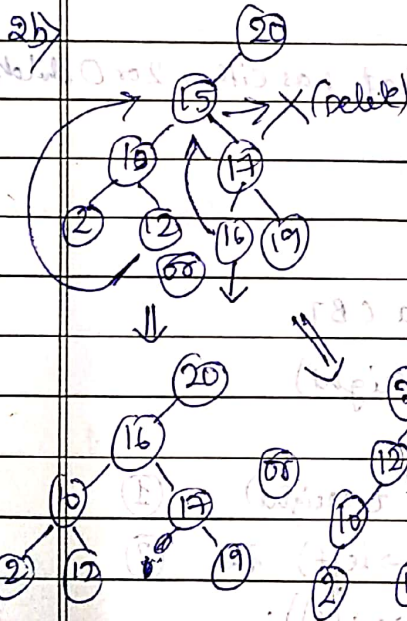
a) one child

b) two children

2 a)



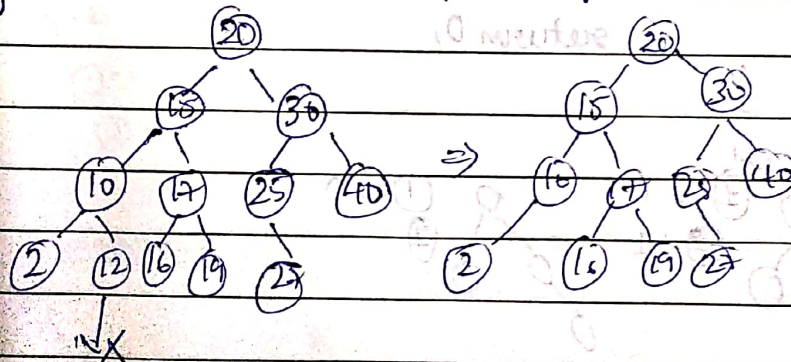
- If a node has one child and we are deleting that node, make that child pointing to grandparent.



- If a node has 2 children, go to right subtree, take least element & replace it.
 (Inorder successor)

- If a node has 2 children, go to left subtree, take greatest element & replace it.
 (Inorder predecessor)

- If a node to be deleted is a leaf, then delete it.



Finding maximum & minimum in a BST
 find_inorder_pre(struct node *t) (1) find_min(struct node *t)

```

    while (t->left)
      t = t->left;
  }

```

find_max(struct node *t)

```

    while (t->right)
      t = t->right;
  }

```

Recursive program on testing whether a tree is
 complete binary tree

Complete binary tree is a tree that has either 2 or 0 children

isComplete(struct node *t)

```

    if (t == NULL)

```

```

        return 1; // is a CBT.

```

```

    if (!t->left && !t->right)

```

```

        return 1;

```

```

    else if (t->left && t->right) (1)

```

```

        return (isComplete(t->left) && (2)
                isComplete(t->right));

```

```

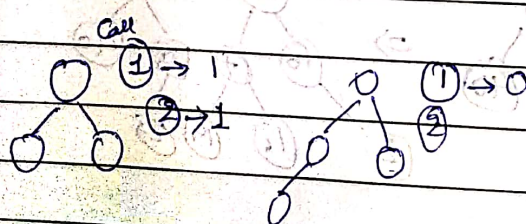
    else

```

```

        return 0;
    }

```

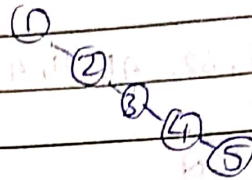


AVL trees

Linked List Search time $O(n)$

Tree reduces time But some cases like

1 2 3 4 5



→ Here time - $O(n)$
Height - $O(n)$

So comes concept of Balancing

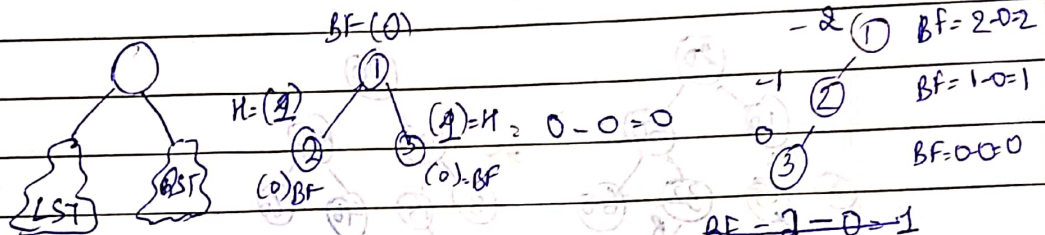
AVL - Balanced tree

It is a balanced BST

Height Nodes - n , Height - $O(\log n)$

Search time - $O(\log n)$

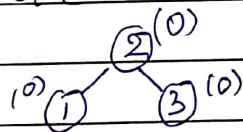
Balance Factor = Height of (LST) - Height (RST)



BF = 2 - 0 = 2

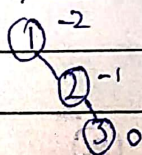
It is called L imbalance

Whenever 1 - L imbalance, rotate clockwise



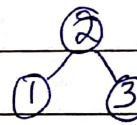
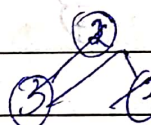
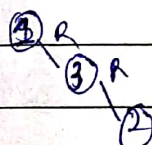
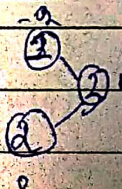
BF = 0

R-R imbalance, In order to balance, rotate anticlockwise

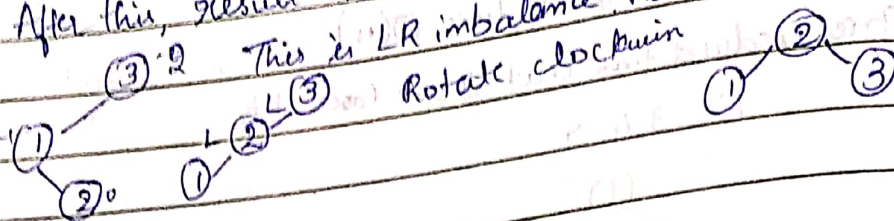


R-L imbalance

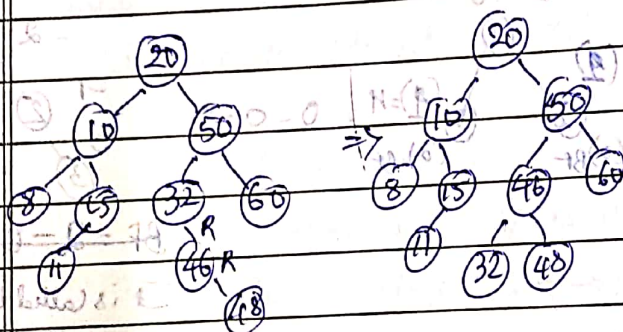
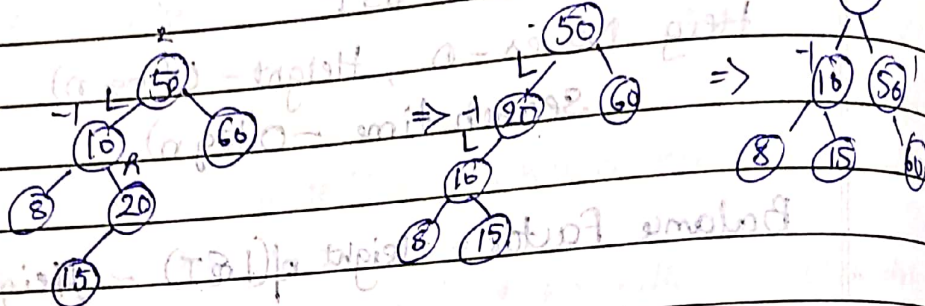
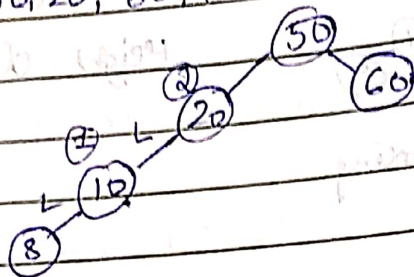
Do 2 rotations. Rotate clockwise. Rotate anticlockwise



After this, result obtained is Binary Search Tree
 This is LR imbalance. Rotate anticlockwise.
 Rotate clockwise

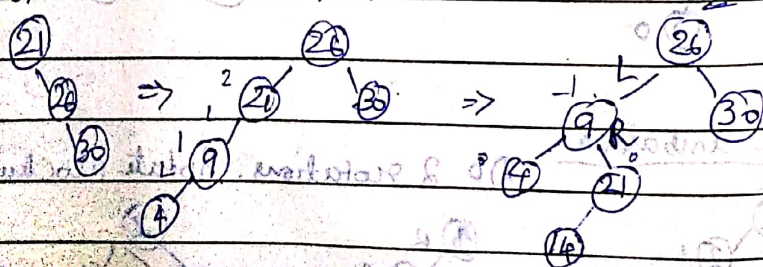


① 50, 20, 60, 10, 8, 15, 32, 46, 11, 48



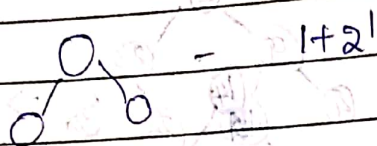
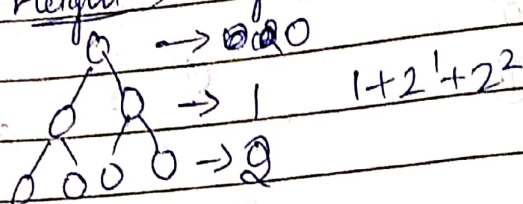
Operations	BST	BBST
Search	$O(n)$	$O(\log n)$
Height	$O(n)$	$O(\log n)$
Insertion	$O(n)$	$O(\log n) + \text{Balancing time}$

21, 26, 30, 9, 4, 14, 28, 18, 15, 10, 2, 3, 7





Maximum & Minimum nodes in an AVL tree of height h

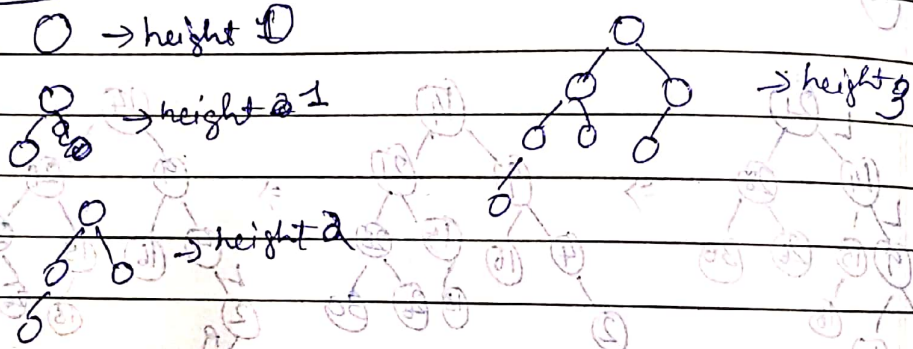


max no. of nodes in a tree of height h
 $1 + 2^1 + 2^2 + 2^3 + \dots + 2^h$

$$\frac{a(r^n - 1)}{r - 1}$$

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

AVL tree



$$N(h) = N(h-1) + 1 + N(h-2)$$

$$= 1, h=0$$

$$= 2, h=1$$

$$= 4$$

$$N(2) = 1 + 1 + 2 = 4$$

$$N(3) = 4 + 1 + 2 = 7$$

Min no. of nodes in height h

Binary tree

Min no. nodes of height $h = h + 1$

7 nodes, max height = 3, min height = 2

12 nodes, max height = 4, min height = 3

GATE 2006

In a binary tree, the number of internal nodes of degree 1 is 5, and number of nodes of degree 2 is 10. The number of nodes in the binary tree is

$$N(n) = N(n-1) - 1 + 2$$

$$N(1) = 2$$

$$N(2) = (2-1) + 2 = 3$$

$$= N(1) - 1 + 2 = 3$$

$$N(3) = 3 - 1 + 2 = 4$$

$$N(n) = N(n-1) + 1$$

$$N(n-2) + 1 + 1$$

$$N(n-3) + 1 + 1 + 1$$

$$N(n) = N(n-k) + k \quad \text{where } n-k=1$$

$$N(1) = N(1) + N(n-1)$$

$$k = n-1$$

$$N(1) = 2 + 0$$

Sol:

$$\text{Degree } 2 \quad n = \text{Degree } n+1$$

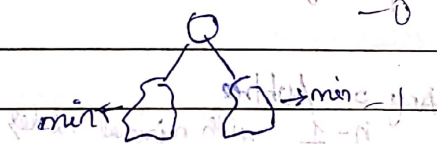
$$10 = 10 + 1$$

$$\therefore 11$$

GATE 2005

In a binary tree, for every node the difference between the number of nodes in the left and right subtree is at most 2.

If the height of tree is $h > 0$, then minimum number of nodes in the tree is



$$N(h) = N(h-1) + 1 + (N(h-1) - 2) \Rightarrow N(h) = 2N(h-1) - 1$$

$$h=1, n=3$$

$$h=2, n=7$$

$$\text{Hence } 2^h$$

substitute for

$$N(2) = 2N(1) - 1 =$$

$$a) 2^{h-1} = 2^{1-1} = 2^0 = 1 \quad \times$$

$$b) 2^{h-1} + 1 = 2^0 + 1 = 2 \quad \checkmark, 2^1 + 1 = 3 \quad \times$$

$$c) 2^h - 1 = 2^1 - 1 = 1$$

$$d) 2^h = 2^1 = 2 \quad \checkmark, 2^2 = 4 \quad \checkmark$$

$$= 2^h N(h-k) - 2^{k-2} - 2^{k-1} = 2^3 N(h-3) - 2^2 - 2^1 = 2^3 (2N(h-2) - 1) - 2^2 - 2^1$$

$$N(h) = 2N(h-1) - 1$$

$$N(h-1) = 2N(h-2) - 1$$

$$N(h-2) = 2N(h-3) - 1$$

$$N(h) = 2(2N(h-2) - 1) - 1$$

$$= 2^2 N(h-2) - 2 - 1$$

$$= 2^2 (2N(h-3) - 1) - 2 - 1$$

$$= 2^3 N(h-3) - 2^2 - 2 - 1$$

$$N(h) = 2^k :$$

$$N(h) = 2^k N(h-k) - 2^{k-1} - 2^{k-2} - \dots - 2 - 1$$

$$= 2^k N(h-k) - (2^{k-1} + 2^{k-2} + \dots + 2 + 1)$$

$$= 2^k N(h-k) - (2^k - 1)$$

$$2^{h-2} N(2) - (2^{h-2} - 1)$$

$$3(2^{h-2}) - (2^{h-2} - 1)$$

$$= 2 \cdot 2^{h-2} + 1$$

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

GATE 1997 and GATE 2005

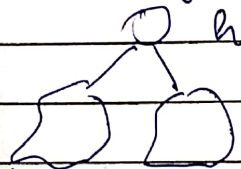
A size balanced binary tree, for every node the difference between the number of nodes in the left and right subtrees is at most 1. If the height of the tree is $h > 0$, then the minimum number of nodes in the tree is and the maximum height

(max dist

of a leaf node from root.) of tree is

88:-

A binary tree of height h has 2^h nodes



Any one subtree $h-1$ with minimal nodes

nodes $n-1$ of left

$$N(h) = N(h-1) + 1 + N(h-1) - 1 \quad // \text{no. of nodes decreased}$$

$$\text{AFL tree } N(h) = N(h-1) + 1 + N(h-2) \quad // \text{no. of height decreased}$$

$$N(h) = 2N(h-1) - 1$$

$$N(h-1) = 2N(h-2) - 1$$

$$N(h-2) = 2N(h-3) - 1$$

$$N(h) = 2^2 N(h-2) - 2^2 - 2 - 1$$

$$N(h) = 2^3 N(h-3) - 2^3 - 2^2 - 2 - 1$$

$$N(h) = 2^k N(h-k) \quad \text{where } h-k \geq 1$$

$$\text{or } k = h-1$$

maximum height with 4 nodes

$$4 = 2^h$$

$$h = 2$$

max height with 8 nodes

$$8 = 2^h$$

$$h = 3$$

$$N(h) = 2^h$$

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



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

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

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

Gate 20 14

(1) Suppose we have a balanced binary search tree 'T' holding n numbers. we are given two numbers 'L' and 'H' and wish to sum up all the numbers in 'T' that lie between L and H.

Suppose there are m such numbers in T. If the tightest upper bound time to compute the sum is $O(n^a \log^b n + m^c \log^d m)$, the value of $a + 10b + 100c + 1000d$ is

L
100

H
200

100-199

$$\rightarrow O(m + \log n)$$

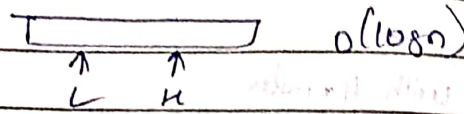
$$c = 1, d = 0, a = 0, b = 0.1$$

$$= 0 + 10(0) + 100(1) + 1000(0)$$

$$= 1100$$

Other method

Inorder (ln)



In worst case for finding L and H it will take $O(\log n)$ time as the given tree is balanced binary search tree. Now there are m elements between L and H. So to traverse m element it will take $O(m)$.
Time (traversal algorithm given below)

Total $(m + \log n)$

$$\Rightarrow a=0, b=1, c=1, d=0$$

$$= 0 + 1b(1) + 100(1) + 1000(0)$$

$$= 110$$

To find all the numbers from L to H, we can do an inorder traversal from root and discard all element before L and after H. But this has $O(n)$ time complexity. So we can do a modification to inorder traversal and combine with Binary search as follows:

- (1) Find L using binary search and keep all nodes encountered in search using stack
- (2) After finding L add it to stack as well and initially $sum = 0$.
- (3) Now, for all nodes in stack, do an inorder traversal starting from their right node & adding the node value to sum. If H is found, stop the algorithm.

Expression trees

$a + b$

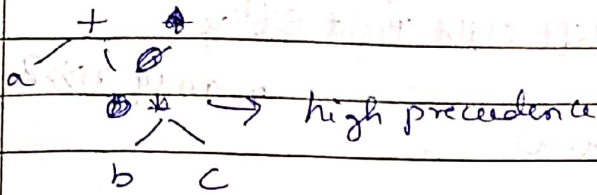


Pre $+ab$

In $a+b$

Post $ab+$

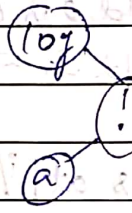
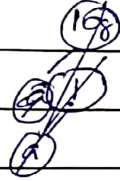
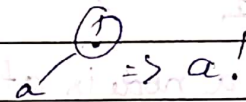
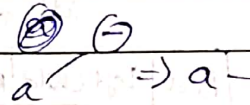
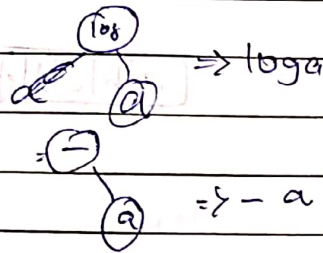
$$a + b * c$$



Pre $+ a * bc$

In $a + b * c$

Post $ab+c \rightarrow abc*+$



GATE 2005

The numbers $1, 2, \dots, n$ are inserted into a BST in some order n . In the resulting tree, the right subtree contains p nodes. The first number to be inserted in the tree must be

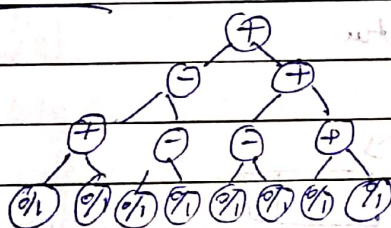
BST - element $(p+1)$ // for BBST & BST

LST - $n - p + 1 = n - p - 1$

Root - $n - p$

GATE 2014

max value to be found

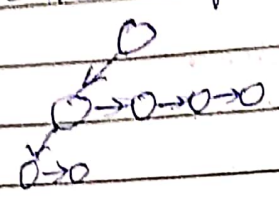


$$\begin{aligned} & ((a+b) - (c-d)) + \\ & \Rightarrow ((e-f) + (g+h)) \\ & = (1+1) - (0-1) + (1-6) \\ & \quad + (1+1) \end{aligned}$$

$$= 2 + 1 + 1 + 2 = 6$$

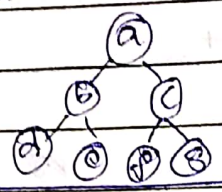
Various representations of a tree

① LC RS → Left child Right Sibling



n array $n \gg 2$

② Array representation → Mainly for heaps



Root	Left child	Right child
1	2	3

a	b	c	d	e	f	g
---	---	---	---	---	---	---

If a node is at i ,

i) left child is at $2i$

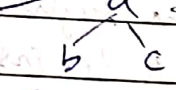
ii) Right child is at $2i+1$

If a node is at i

i) parent is at $\lfloor i/2 \rfloor$

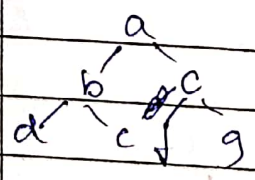
n elements, $2^n - 1 \rightarrow$ array size

③ Nested representation



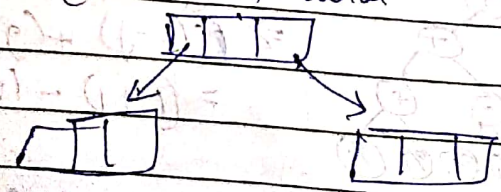
(a b a c)
L R R L

④ (Root Left Right)
(a b c)



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

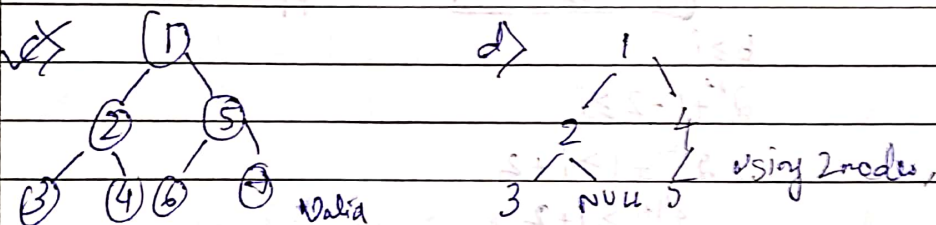
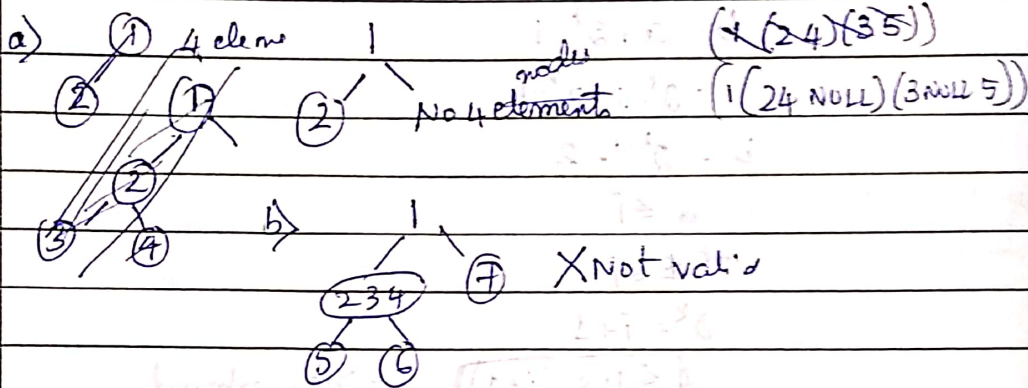
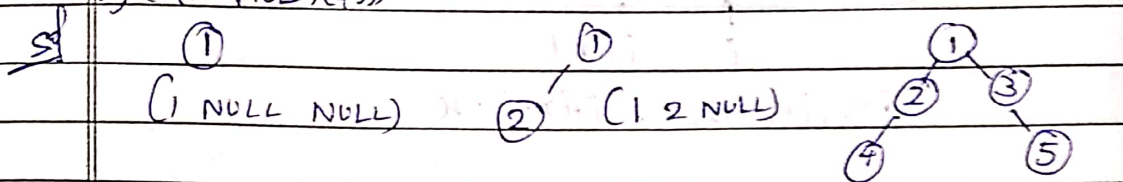
④ Normal (pointer & structure)



GATE 2000

Consider the following nested representation of binary trees: (XYZ) indicates Y & Z are the left & right subtrees, respectively, of node X. Note that Y & Z may be NULL, or further nested. Which of the following represents a valid binary tree?

- a) (12(4567))
 b) ((234)56)7)
 c) (1(234)(567))
 d) (1(23 NULL)(45))

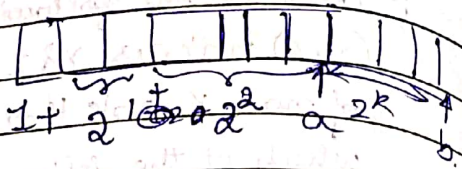
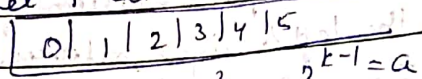
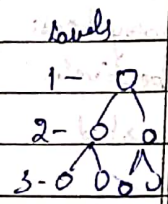
GATE 2006

An array X of n distinct integers is interpreted as a complete binary tree. The index of the first element of the array is 0.

1) The index of the parent element $X[i]$, $i \neq 0$ is $\lfloor i/2 \rfloor$

2) If only the root node does not satisfy the heap property, the algorithm to convert the binary heap into heap has the best asymptotic time complexity of $O(\log n)$ because we have to heapify whole heap i.e., $O(\log n)$ is height of heap

3) If the root node is at level 0, the level of element $X[i], i \neq 0$,
 let i at level ' k '



$$2^0 + 2^1 + 2^2 + \dots + 2^{k-1} = a$$

$$\frac{1(2^k - 1)}{2 - 1} = a$$

$$a \leq i \leq b$$

$$a = 2^k - 1$$



$$i+0, i+1, i+2, \dots, i+(2-1) = 2^k$$

$$b = a + 2^k - 1$$

$$= 2^k - 1 + 2^k - 1$$

$$b = 2^{k+1} - 2$$

$$a \leq i$$

$$2^k - 1 \leq i$$

$$2^k = i + 1$$

$$\boxed{k \leq \log_2(i+1)} \rightarrow \text{Upperbound}$$

$$b \geq i$$

$$2^{k+1} - 2 \geq i$$

$$2^{k+1} + 1 \geq i + 2$$

$$2^{k+1} \geq i + 2$$

$$k+1 \geq \log_2(i+2) - 1$$

$$k \geq (\log_2(i+2) - 1) \rightarrow \text{Lowerbound}$$

There can be only one integer b/w these bounds

$$\lfloor \log_2(i+1) \rfloor \text{ and } \lceil \log_2(i+2) - 1 \rceil$$

Graphs

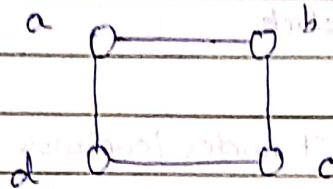
SURYA Gold

Date

Page

- 1) World wide web is represented as a graph
- 2) Social Network
 - 3) Person $\rightarrow$ Nodes, Friend $\rightarrow$ Edge b/w a person & his friend
 - Friends $\rightarrow$ Nodes
- 1) webpage $\rightarrow$ Node
- Links $\rightarrow$ Edge
- Adjacency list in a graph $\rightarrow$ friend list in a facebook
- Mutual friend suggestion - BFS

Representation of Graphs



Adjacency matrix

	a	b	c	d
a	0	1	0	1
b	1	0	1	0
c	0	1	0	1
d	1	0	1	0

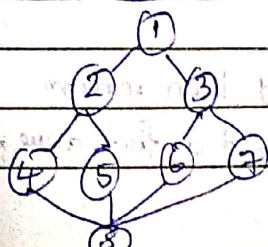
Adjacency List $\rightarrow$ Useful for large/dense graphs

a	$\rightarrow$ [b] $\rightarrow$ [d] 0
b	$\rightarrow$ [a] $\rightarrow$ [c] 0
c	$\rightarrow$ [b] $\rightarrow$ [d] 0
d	$\rightarrow$ [a] $\rightarrow$ [c] 0

Dense graph - If the no. of edges in a graph is equal to number order of nodes

No. of elements = $2 \times E$ in undirected graph in Adjacency List
 $= E$ in directed graph
 $= O(V+E) \rightarrow$ Adjacency List
 $O(V^2) \rightarrow$ Adjacency matrix

Introduction to BFS and DFS



Visited $\rightarrow$ I found it

Explored $\rightarrow$ I found it & its adjacent vertices

Visited0 $\rightarrow$ Not visited1 $\rightarrow$ VisitedBoth BFS & DFS uses
array to keep track of
visited nodesDFS algorithm keeps track of unexplored nodes
using stack

BFS

using queue

Space complexity $\rightarrow$ Atleast $O(n)$ BFS $\rightarrow O(n) \rightarrow$ queueDFS $\rightarrow O(n) \rightarrow$ stack

Breadth first search visit nodes levelwise (horizontally)

Depth first search visit nodes depthwise (vertically)

BFS algorithm

BFS(v)

// The graph G and array visited[] are global
visited[] is initialized to 0

{

u = v;

repeat:

{

for all vertices w adjacent to u do

{

if (visited[w] == 0)

{

add w to queue;

visited[w] = 1;

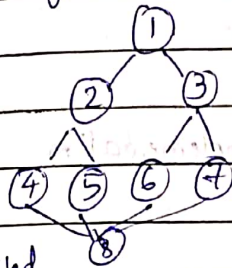
}

If a queue is empty then return

Delete the next element u from queue;

}

Tracing



Visited

1	0	0	0	0	0	0	0
1	2	3	4	5	6	7	

 $\rightarrow O(n)$ $u=1$ $w = \{2, 3\}$

Queue

2	3
---	---

 $(n-1) \rightarrow O(n)$

Visited

1	1	1	1	1	1	0	0
1	2	3	4	5	6	7	

Visited

1	1	0	0	0	0	0	0
1	2	3	4	5	6	7	8

Queue

4	7	8
---	---	---

 $u=6$ $v = \{3, 8\}$

Queue

2	3
---	---

 $u=2$ $w = \{1, 4, 5\}$

Visited

1	1	1	1	1	1	1	0
---	---	---	---	---	---	---	---

Queue

3	4	5
---	---	---

Visited

1	1	1	0	0	0	0	0
1	2	3	4	5	6	7	8

Queue

2	8
---	---

 $u=7$ $w = \{3, 8\}$

Queue

3	4	5
---	---	---

 $u=3$ $w = \{1, 6, 7\}$

Return Visited

1	1	1	1	1	1	1	1
1	2	3	4	5	6	7	8

Queue

4	5	6	7
---	---	---	---

Visited

1	1	1	1	0	0	0	0
1	2	3	4	5	6	7	8

Queue

8

 $u=8$ $w = \{4, 5, 6, 7\}$

Queue

4	5	6	7	8
---	---	---	---	---

 $u=4$ $v = \{2, 8\}$

Orders of visit

(1) 2, 8, 6, 7, 4, 5, 8

(2) 2, 3, 4, 5, 6, 7, 8

We can get more than 1 orders

Visited

1	1	1	1	0	0	0	0
---	---	---	---	---	---	---	---

Queue

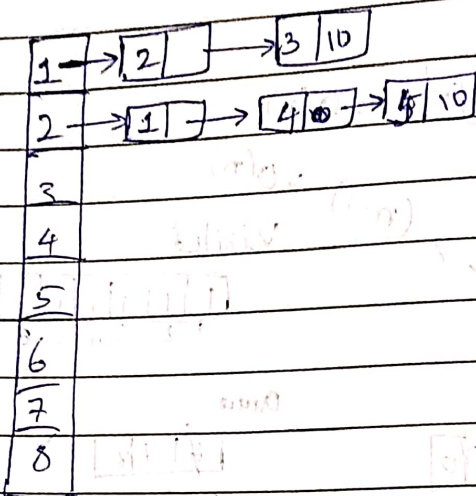
5	6	7	8
---	---	---	---

 $u=5$ $v = \{2, 8\}$

BFS analysis in case of linked list

Space complexity - $O(n)$

Time complexity - depends on implementation



$O(2E) \rightarrow$ undirected graph

$O(E) + O(V) \rightarrow$ Time complexity

Space complexity $\rightarrow O(V)$

BFS analysis in case of Adjacency matrix

1 2 3 4 5 6 7 8

1								
2								
3								
4								
5								
6								
7								
8								

Space complexity $\rightarrow O(V)$

Time complexity $\rightarrow O(n^2)$

$\rightarrow O(V^2)$

Initialization $\rightarrow O(V^2 + V) \rightarrow O(V^2)$

Breadth First Traversal using BFS

BFS(G, n)

{

for $i=1$ to n do

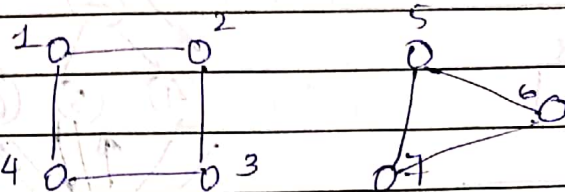
visited[i] = 0;

for $i=1$ to n do

if (visited[i] = 0)

then BFS(i);

}



visited | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
 1 2 3 4 5 6 7

visited | 1 | 1 | 1 | 1 | 0 | 0 | 0 |

call BFS(5)

visited | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Time complexity - $O(E+V)$

Space complexity - $O(V)$

DFS algorithm

DFS(v)

{

visited[v] = 1;

for each vertex w adj to v do

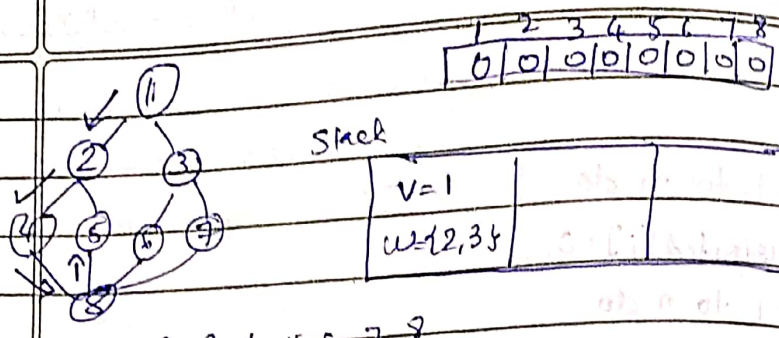
{

if (visited[w] = 0) then

DFS(w)

}

}



Stack

V=1	
W={2,3}	

Visited

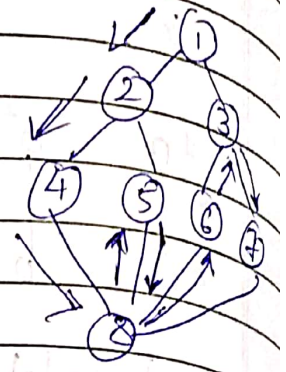
1	2	3	4	5	6	7	8
1	0	0	0	0	0	0	0

Stack

V=1	V=2	V=4
W={2,3}	W={1,4,5}	

Visited

1	2	3	4	5	6	7	8
1	1	0	0	0	0	0	0



Stack

V=1	V=2	V=4
W={2,3}	W={1,4,5}	W={2,8}

Visited

1	2	3	4	5	6	7	8
1	1	0	1	0	0	0	0

Stack

V=1	V=2	V=4	V=8
W={2,3}	W={1,4,5}	W={2,8}	W={4,5,6,7}

Visited

1	2	3	4	5	6	7	8
1	1	0	1	0	0	0	1

Stack

V=1	V=2	V=4	V=8	V=5
W={2,3}	W={1,4,5}	W={2,8}	W={4,5,6,7}	W={2,8}

Visited

1	2	3	4	5	6	7	8
1	1	0	1	1	0	0	1

Stack

V=1	V=2	V=4	V=8	V=5
W={2,3}	W={1,4,5}	W={2,8}	W={4,5,6,7}	W={2,8}

Stack

V=1	V=2	V=4	V=8	V=6
W={2,3}	W={1,4,5}	W={2,8}	W={4,5,6,7}	W={3,8}

Visited

1	2	3	4	5	6	7	8
1	1	0	1	1	1	0	1

Stack

$v=1$	$v=2$	$v=4$	$v=8$	$v=6$	$v=3$
$w=\{2,3\}$	$w=\{1,4,5\}$	$w=\{2,8\}$	$w=\{4,5,6,7\}$	$w=\{3,8\}$	$w=\{1,6,7\}$

Visited

1	2	3	4	5	6	7	8
1	1	1	1	1	1	0	1

Stack

$v=1$	$v=2$	$v=4$	$v=8$	$v=6$	$v=3$	$v=7$
$w=\{2,3\}$	$w=\{1,4,5\}$	$w=\{2,8\}$	$w=\{4,5,6,7\}$	$w=\{3,8\}$	$w=\{1,6,7\}$	$w=\{3,8\}$

Visited

1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1

Stack

$v=1$	$v=2$	$v=4$	$v=8$	$v=6$	$v=3$	$v=7$
$w=\{2,3\}$	$w=\{1,4,5\}$	$w=\{2,8\}$	$w=\{4,5,6,7\}$	$w=\{3,8\}$	$w=\{1,6,7\}$	$w=\{3,8\}$

⑦

⑥

⑤

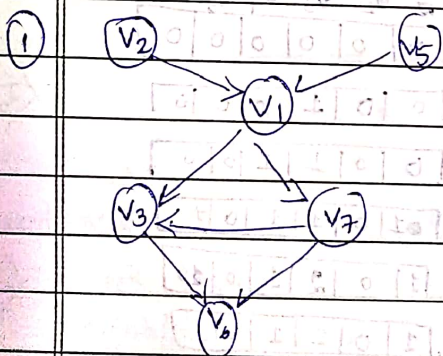
④

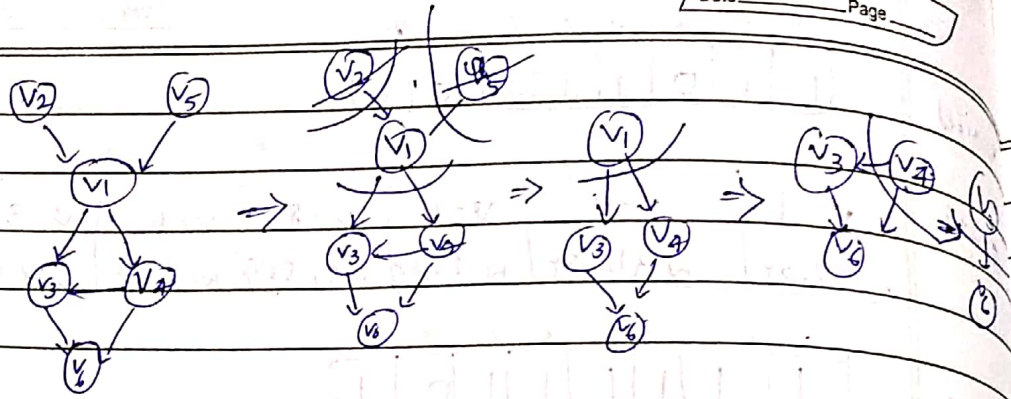
③

②

①

Popping order

Space complexity - $O(V)$ Time complexity - $O(V+E)$ → Adjacency List +
 $O(V^2)$ → Adjacency matrixTopological SortInput: Directed Acyclic graphOutput: $i \rightarrow j$, i should be first in order i.e., sorted



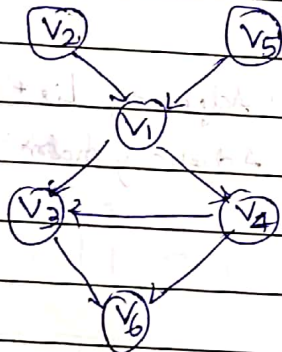
Order:- $V_2, V_5, V_1, V_4, V_3, V_6$
 $V_5, V_2, V_1, V_4, V_3, V_6$

Approach-1

Step 1:- Identify vertices that has no incoming edges

Step 2:- Delete this vertex of indegree 0 and all its outgoing edges from the graph. Place it in the output

Step 3:- Repeat step 1 & 2 until graph is empty



Above method:- Traversal

Step 1

Time complexity:- $O(V) \times V = O(V^2)$

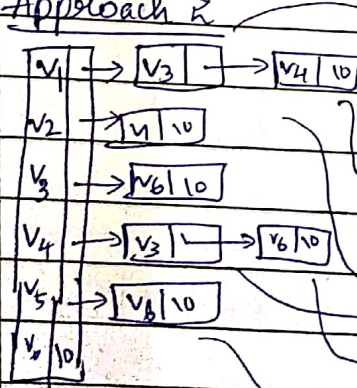
Step 2:- $O(E)$

Overall:- $O(V^2 + E)$

It can be reduced to $O(V + E)$

Space complexity:- $O(1)$

Approach 2



Array

	1	2	3	4	5	6
0	0	0	0	0	0	0

Step 1

	1	2	3	4	5	6
0	0	0	1	0	0	0

Step 2

	1	2	3	4	5	6
0	0	0	1	1	0	0

Step 3

	1	2	3	4	5	6
0	1	0	1	1	0	1

	1	2	3	4	5	6
1	0	2	1	0	0	0

	1	2	3	4	5	6
1	0	2	1	0	1	1

	1	2	3	4	5	6
2	0	2	1	0	2	2

Time complexity:- $O(V + E) \rightarrow$ No. of entries in A.L.

Step 1:- Print highest incoming degree

Step 2: Get into vertices previously connected deleted

Repeat 2 until graph is empty

1	2	3	4	5	6
1	-1	2	1	0	2

V_2

1	2	3	4	5	6
0	-1	2	1	0	2

V_2, V_3

1	2	3	4	5	6
0	-1	2	1	-1	2

V_2, V_5, V_1

1	2	3	4	5	6
-1	-1	1	0	-1	2

V_2, V_5, V_1, V_4

1	2	3	4	5	6
-1	-1	0	-1	-1	1

V_2, V_5, V_1, V_4, V_3

1	2	3	4	5	6
-1	-1	-1	-1	-1	0

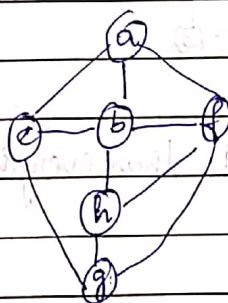
$V_2, V_5, V_1, V_4, V_3, V_6$

1	2	3	4	5	6
-1	-1	-1	-1	-1	-1

Time complexity $\rightarrow O(V+E) \rightarrow$ Topological sort.

① GATE 2003

DFS on



I $\rightarrow$ a b e g h f

II $\rightarrow$ a b f e g h

III $\rightarrow$ a b f h g e

IV $\rightarrow$ a f g h b e

So I, III, IV are DFS

I $\rightarrow$

$v=a$	$v=b$	$v=c$	$v=g$	$v=h$	$v=f$
$w=\{e, b, f\}$	$w=\{a, e, f, h\}$	$w=\{a, g, h\}$	$w=\{e, h, f\}$	$w=\{b, f, g\}$	

II not possible

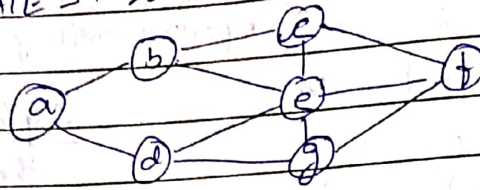
III $\rightarrow$

$v=a$	$v=b$	$v=f$	$v=h$	$v=g$	$v=e$
$w=\{e, b, f\}$	$w=\{a, e, f, h\}$	$w=\{e, b, f, g\}$	$w=\{b, f, g\}$	$w=\{e, h, f\}$	$w=\{a, g, b, f\}$

IV $\rightarrow$

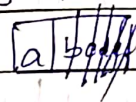
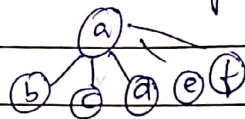
$v=a$	$v=f$	$v=g$	$v=h$	$v=b$	$v=e$
$w=\{e, b, f\}$	$w=\{a, b, f, g\}$	$w=\{a, e, f, h\}$	$w=\{b, f, g\}$	$w=\{a, e, f, h\}$	$w=\{a, g, b, f\}$

② GATE IT 2008

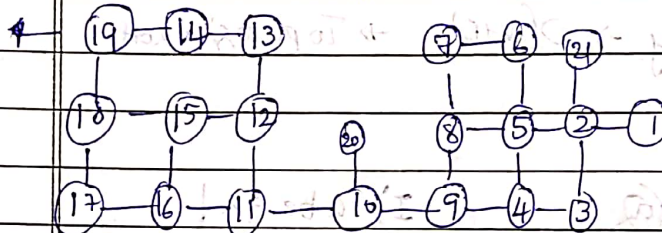


- (direct)
- (a) a b e f d g c → Check connectivity of graph X
 (b) a b e f c g d ✓
 (c) a d g e b c f - ✓
 (d) a d b c g e f - X

DFS → n-1 of elements BFS queue of 2 cb



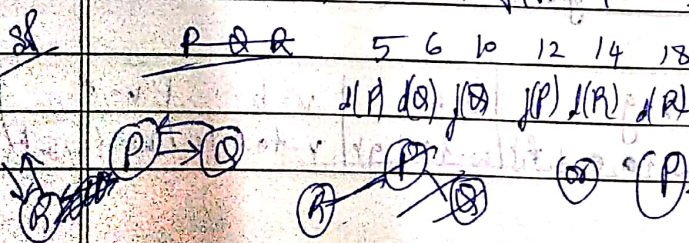
③ GATE 2014 → A graph without number given. We shall number it



Depth of recursion stack → 19, then everything gets popped of

④ GATE 2006

Consider a DFS of an undirected graph with 3 vertices P, Q, R. Let discovery time $d(u)$ represent the time instant when the vertex 'u' is first visited, and finish time $f(u)$ represent the time instant when vertex 'u' is last visited. Given that $d(P) = 5$ units, $f(P) = 12$ units, $d(Q) = 6$ units, $f(Q) = 10$ units, $d(R) = 14$ units, $f(R) = 18$ units. What is true about graphs



Two components of graph
 ∴ P is finished before calling R

Hashing

SURYA Gold

Date _____ Page _____

Searching (Worst case)

Unsorted Array	$O(n)$
Sorted Array	$O(\log n)$
Linked List	$O(n)$
Binary Tree	$O(n)$
Binary Search Tree	$O(\log n) \Rightarrow O(n)$
ABST	$O(\log n)$
Priority Queue	$O(n)$ $O(1) \rightarrow \text{min/max}$

Hashing reduces search time. It is order $O(1)$

Direct Address Table

Each record has unique key you have to know key value.
we can store it in array

Separate arrays for record & key to be maintained

Fails when values are large

Introduction to Hashing

1) Chaining $\rightarrow$ No restriction on no. of elements
Requires more space since we maintain a linked list.

2) Open Addressing

Inserts within table, No. element must be of table size.

(Chaining $\rightarrow$ Deletions easier)

OA $\rightarrow$ Insertion, Searching

Insertion, Deletion, Searching - constant time in Hashing

Chaining $\rightarrow$ Worst case $O(n)$

Average case - $O(1 + n/m)$

Load factor $\alpha = \frac{n}{m} = \frac{\text{Elements in Hash table}}{\text{Size of hash table}}$

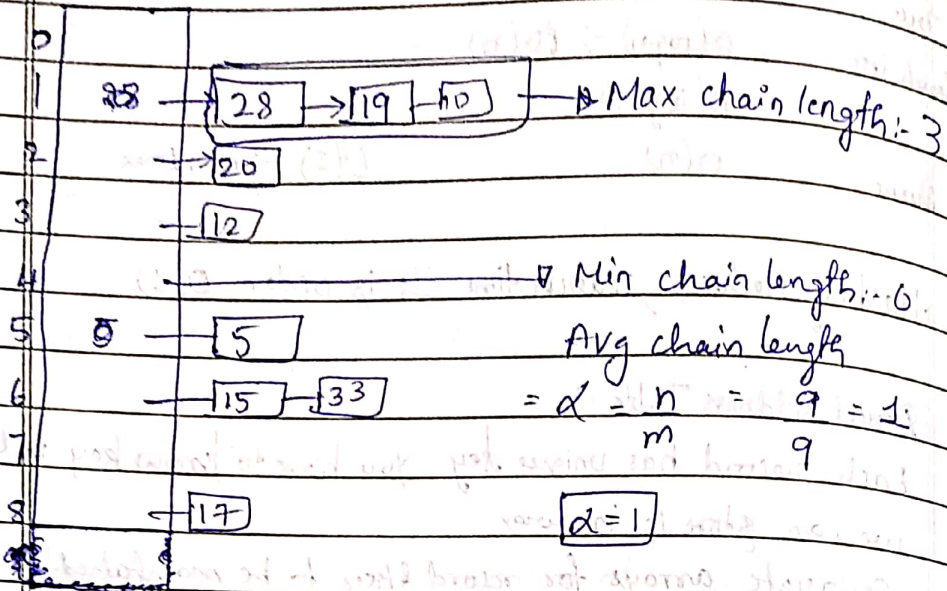
$n = K * m$ K is constant

$\alpha = K$

GATE 2014

- (1) $h(k) = k \bmod 9$. Hash Table has 9 slots, chaining is used. Keys: 5, 28, 19, 15, 20, 33, 12, 17, 10. Then max, min & average chain lengths in hash table

Ans:



- (2) Consider a hash table with 100 slots. Collisions are resolved using chaining. Assume simple uniform hashing. What is the probability that the first 3 slots are unfilled after 3 insertions

Ans:

$$100 - 3 = 97 \quad \text{RBA} \quad \text{ME}$$

$$\left(\frac{97}{100}\right) \left(\frac{97}{100}\right) \left(\frac{97}{100}\right) = \frac{95 \times 96 \times 97}{100^3}$$

- (3) Consider a hash table with n buckets, where chaining is used to resolve collisions. The hash function is such that the probability that a key value is hashed to a particular bucket is $1/n$. The hash table is initially empty & k distinct values are inserted in the table

- What is the probability that bucket number '1' is empty after k insertions
- What is the probability that no collision has occurred in any one of k insertions
- What is the probability that first collision occurs at k^{th} insertion

$$d) \textcircled{a} \left(\frac{n-1}{n}\right) \left(\frac{n-1}{n}\right) \dots \left(\frac{n-1}{n}\right) \\ = \left(\frac{n-1}{n}\right)^k$$

$$\textcircled{b} \left(\frac{n}{n}\right) \left(\frac{n-1}{n}\right) \left(\frac{n-2}{n}\right) \dots \left(\frac{n-(k-1)}{n}\right)$$

$$\textcircled{c} \left(\frac{n}{n}\right) \frac{k-1}{n}$$

Open Addressing

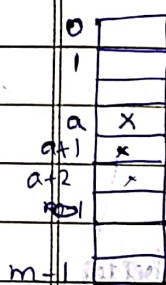
Time Complexity - $O(n) \rightarrow$ Worst case

$O(1) \rightarrow$ Average case

Deletions is troublesome

$$h(k) = U \rightarrow \{0, \dots, m-1\}$$

Linear Probing



$$h(k): U \rightarrow \{0, \dots, m-1\}$$

$$h(k) = a + (h(k) - a) \cdot n$$

$$h'(k, i) = (h(k) + i) \bmod m$$

$$h'(k, 1) = (a + 1) \bmod m$$

$$h'(k, 2) = (h(k) + 2) \bmod m$$

$$= (a + 2) \bmod m$$

We search till we get free slot

$$i = \{0, 1, 2, \dots, m-1\}$$

We probe only m -times if there are m slots in the table

Problems: ① Secondary clustering $\rightarrow$ It is a problem in which both elements start from same i & then probing is same for both

② Primary clustering $\rightarrow$ It is a problem in which many elements cluster in a particular part of hash table



Primary clustering

Filled by probability

i/m & but has higher probability

the next element after filled slots

Search time: $O(1)$ or $O(2)$

Disadvantage: Search entire cluster until find an empty space

Quadratic Probing

$$h'(k, i) = (h(k) + c_1 i + c_2 i^2) \bmod m$$

Next probe position is quadratic

Probe position increases quadratically

Avoids (1) Primary clustering

Primary clustering is a process in which a block of data is formed in the hash table when collision is resolved

Eg: $m=10, (0 \dots 9), c_1=1, c_2=1,$

$$h(k) = k \bmod 10$$

1	x
3	x
6	x
11	

$$h'(k, 1) = 1 + 1 + 1$$

$$h'(k, 5) = 1 + 1 + 25$$

$$= 3$$

$$= 27$$

$$h'(k, 2) = 1 + 2 + 4$$

$$h'(k, 6) = 1 + 1 + 36$$

$$= 6$$

$$= 37$$

$$h'(k, 3) = 1 + 1 + 9$$

$$h'(k, 7) = 1 + 1 + 49$$

$$= 11$$

$$= 51$$

$$h'(k, 4) = 1 + 1 + 16$$

$$h'(k, 8) = 1 + 1 + 64$$

$$= 18$$

$$= 66$$

$$h'(k, 9) = 1 + 1 + 81 = 83$$

Problem: - Whole (Entire) table is not examined

Wisely choose c_1, c_2, m

Make c_1 & c_2 dependent on key, then it's better

Double Hashing

Avoids (1) Primary clustering (2) Secondary clustering

Successive probes depends on keys and does not following same sequence if initial probe position is same

$$h'(k) = (h_1(k) + i h_2(k)) \bmod n$$

Choose m, k are relatively prime

$$h_2(k) \rightarrow \text{odd} < m$$

$$m \rightarrow 2^k$$

Load factor α

Probability of collision = $\frac{\text{No. of slots filled in hash table}}{\text{Size of hash table}}$

- (1) Consider a hash table that distributes key uniformly. The hash table size is 20. After hashing of how many keys will the probability that any new key hashed collides with an existing one exceed 0.5

$$sl: \frac{i}{20} \geq 0.5 \quad \frac{i}{m} \geq 0.5$$

$$i = 10$$

- (2) How many different insertion sequences of the key values using the same hash function and linear probing will result in the hash table shown above

0	
1	
2	42
3	23
4	34
5	52
6	46
7	33
8	
9	

4 elements 42, 23, 34, 46

are in their positions

2 elements 52, 33 are probed

$(42, 23, 34) \rightarrow 52, 33$

46 $\rightarrow$ 5 ways

42, 23, 34 $\rightarrow$ 3! ways

$$3! \times 5 = 6 \times 5$$

$$= 30 \text{ ways}$$

Recursion

```

1. A(n)
{
2. if (n > 0)
3. printf("%d", n-1)
4. A(n-1)
5. }
}

```

P
A

```

main() {
A(3)
}

```

Activation record is created on calling each function in stack

Stack

	A(3)	A(2)	A(1)	A(0)
main()	n=3	n=2	n=1	n=0
	5	5	5	
main()	A(3)	A(2)	A(1)	A(0)
main()	A(3)	A(2)	A(1)	
main()	A(3)	A(2)		
main()	A(3)			
main()				

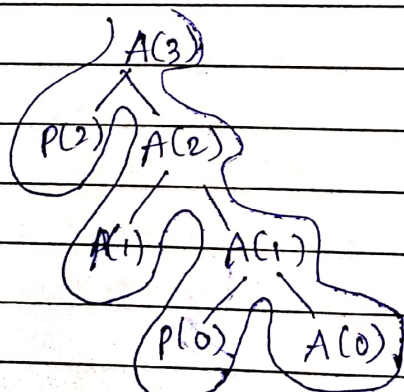
Instruction pointer points to 5 which is next instruction to be executed
n is local variable

A(0) returns without doing anything. Then A(1) is called. We have to go to line no. 5. & same continues
main() is called & gets finished.

2 1 0

Space complexity :- Stack records = n+1
Space = O(n)

Time complexity :- T(n) = C + T(n-1)
= O(n) 5 Activation records are created



Depth of tree = n+1
= Max length of stack records

(2)

 $A(n)$

{

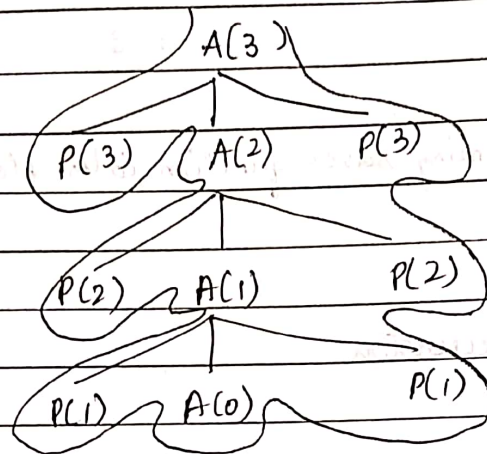
if ($n > 0$)

{

 $P(n)$; $A(n-1)$; $P(n)$;

}

}



$$T(n) = C + T(n-1)$$

$$= O(n)$$

$$O/P:- 3 \quad 2 \quad 1 \quad 1 \quad 2 \quad 3$$

$$\text{Stack records} = n+1$$

$$= O(n)$$

(3)

 $A(n)$

{

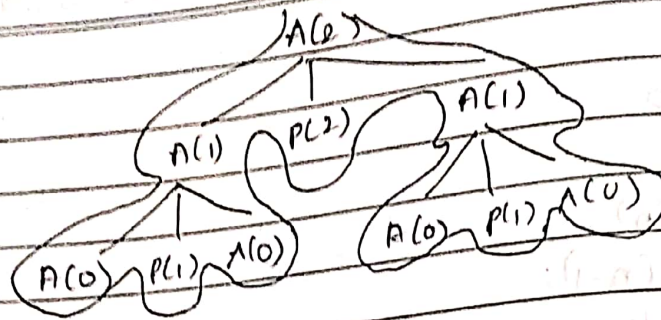
if ($n > 0$)

{

 $A(n-1)$ $P(n)$ $A(n-1)$

}

}



1 2 1

A(0)	A(0), A(0)	No. of stack records = n+1
A(1)	A(1)	= 2+1
A(2)		= 3

Dynamic programming saves function calls. Hence saving time

Analysing the recursion

f(n)

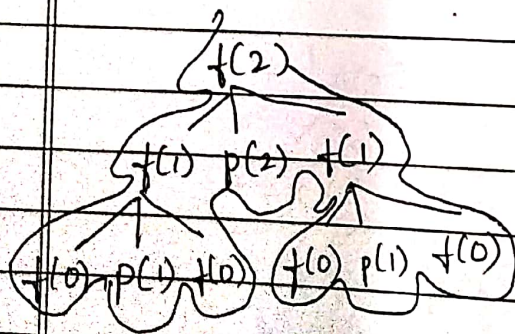
{

if(n==0)
return;

f(n-1);
printf(n);

f(n-1);

}



1 2 1

No. of function calls

f(1) = 3

f(2) = 7

f(3) = 15

$f(n) = 2^{n+1} - 1$

F(n) = No. of times f(n) called

$F(n) = 2F(n-1) + 1$

1 - already calling

$$\begin{aligned}
 F(n) &= 2F(n-1) + 1 & F(n-1) &= 2F(n-2) + 1 \\
 &= 2[2(F(n-2) + 1) + 1] & F(n-2) &= 2F(n-3) + 1 \\
 &= 2[2(2(F(n-3) + 1) + 1) + 1] \\
 &= 2^2 F(n-2) + 2 + 1 \\
 &= 2^3 F(n-3) + 2^2 + 2 + 1 \\
 &= 2^i F(n-i) + 2^{i-1} + 2^{i-2} + \dots + 2^0
 \end{aligned}$$

$$F(n) = 1, n=0$$

$$\begin{aligned}
 n-i &= 0 \\
 i &= n
 \end{aligned}$$

$$\begin{aligned}
 &= 2^n F(0) + 2^{n-1} + 2^{n-2} + \dots + 1 \\
 &= 2^n \cdot 1 + 2^{n-1} + 2^{n-2} + \dots + 1 \\
 &= 2^n + 2^{n-1} + 2^{n-2} + \dots + 1
 \end{aligned}$$

It is in Geometric Progression

$$a(r^{n+1} - 1)$$

$$r-1$$

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

$$2-1$$

$$F(n) = 2^{n+1} - 1$$

Time Complexity =

$$T(n) = 2T(n-1) + 1$$

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

$$= O(2^n)$$

Space Complexity = $O(n)$. Since depth of tree is Order of n

Gate 2001

```
void abc(char *s)
```

```
{
```

```
    if (s[0] == '\0') return;
```

```
    abc(s+1);
```

```
    abc(s+1);
```

```
    printf("%c", s[0]);
```

```
}
```

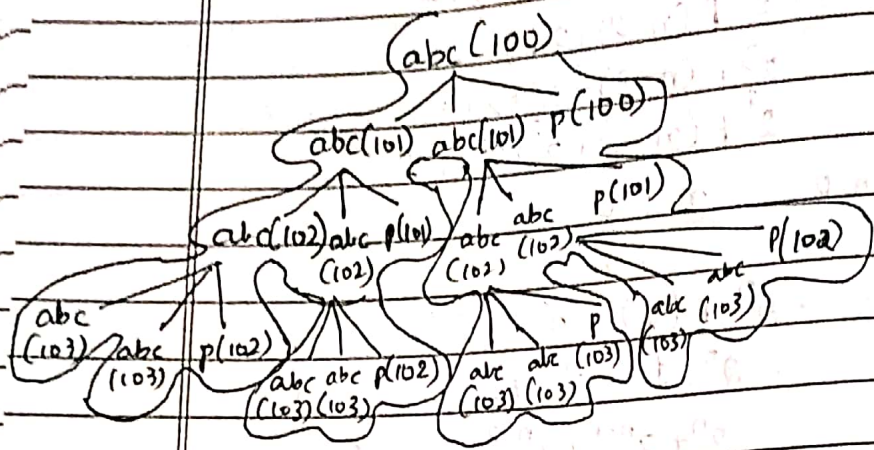
```
main() {
```

```
    abc("123");
```

```
}
```

a) In memory it is stored as

1	2	3	10
100	101	102	103



O/p :- 3 3 2 3 3 2 1

b) If $abc(s)$ is called with a null terminated string 's' of length 'n' characters (not counting null '\0' character).

How many characters will be printed by $abc(s)$

$C(n)$ - no. of characters printed by giving input of n character

$$C(n) = 2C(n-1) + 1$$

Just above use back substitution method

$$C(n) = 2^3 C(n-3) + 2^2 + 2^1 + 2^0$$

$$= 2^i (n-i) + 2^{i-1} + 2^{i-2} + \dots + 1$$

$$n-i=1 \quad (\because C(1)=1)$$

$$= 2^{n-1} C(1) + 2^{n-2} + 2^{n-3} + \dots + 1$$

$$= \frac{a(r^{n+1}-1)}{r-1}$$

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

$$C(n) = 2^n - 1$$

$C(1) = 1$ char

$C(2) = 3$ char

$C(3) = 7$ char

(Cross verify with a)

Gyak 2004

int rec(int n)

{


```
if (n == 1)
```

```
return
```

```
else
```

```
return (rec(n-1) + rec(n-1))
```

$$T(n) = 1 + 2T(n-1)$$

$$T(n) = 1 \text{ if } n = 1$$

$$T(n) = 2^i T(n-i) + 2^{i-1} + 2^{i-2} + \dots + 1$$

$$n-i=1 \quad T(n) = 2^{n-1} T(1) + 2^{n-2} + 2^{n-3} + \dots + 1$$

$$= 2^{n-1} + 2^{n-2} + 2^{n-3} + \dots + 1$$

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

$$2-1$$

$$T(n) = 2^n - 1$$

$$T(n) = O(2^n)$$

Contd.

Gate 2005

```
void foo(int n, int sum)
```

```
{
```

```
1 int k=0, j=0;
```

```
2 if (n==0) return
```

```
3 k=n/10, j=n/10;
```

```
4 sum=sum+k;
```

```
5 foo(j, sum)
```

```
6 printf("%d", k);
```

```
}
```

```
int main()
```

```
{
```

```
int a = 2048, sum = 0;
```

```
foo(a, sum);
```

```
printf("%d", sum);
```

```
}
```

main	foo	foo	foo	foo	foo
n=2048	n=2048	n=204	n=20	n=2	n=0
sum=0	sum=08	sum=812	sum=12	sum=14	sum=14
k=0	k=8	k=4	k=0	k=2	k=0
j=0	j=204	j=20	j=2	j=0	j=0

20480

Gate 2010

```
int f(int *a, int n)
{
```

```
    if (n <= 0)
```

```
        return 0;
```

```
    else
```

```
        if (*a % 2 == 0)
```

```
            return *a + f(a+1, n-1);
```

```
        else
```

```
            return *a - f(a+1, n-1);
```

```
    }
```

```
int main() {
```

```
    int a[] = {12, 7, 13, 4, 11, 6}
```

```
    printf("%d", f(a, 6));
```

```
    return 0;
```

```
}
```

100	102	104	106	108	110
12	7	13	4	11	6

f(a, 6)

→ f(100, 6)

↓
12 % 2 == 0

12 + f(102, 5)

↓
7 % 2 == 0

↓
7 - f(104, 4)

↓
13 % 2 == 0

↓
13 - f(106, 3)

$$4 \div 2 = 0$$

$$4 + \downarrow (108, 2)$$

$$\downarrow$$

$$11 \div 2 = 0$$

$$11 - \downarrow (1100, 2)$$

$$6 \div 2 = 0$$

$$6 + \downarrow (112, 0)$$

$$6 + 0 = 6$$

$$\cancel{12+7} - 13 - \cancel{4} - \cancel{11} - 6$$

$$4 + 5$$

$$13 - 9$$

$$7 - 4$$

$$12 + 3$$

$$= 15$$

$$12 + (7 - (13 - (4 + (11 - (6 + (0))))))$$

$$11 - 6$$

$$4 + 5$$

$$13 - 9$$

$$7 - 4$$

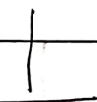
$$12 + 3$$

$$= 15$$

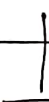
Tower of Hanoi



x

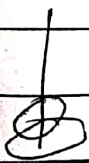


y



z

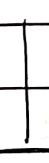
①



x

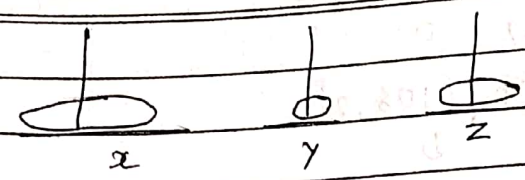


y

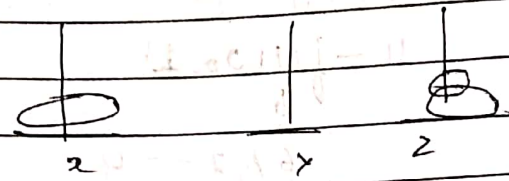


z

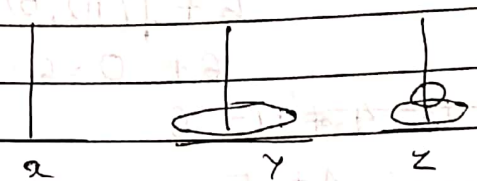
②



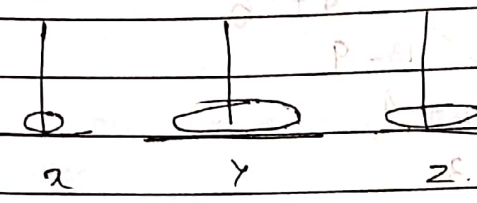
③



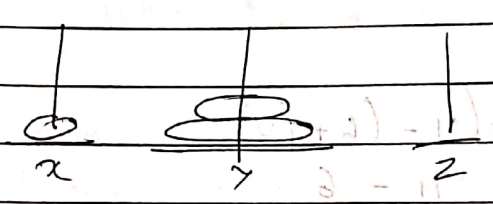
④



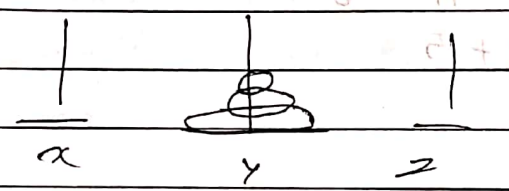
⑤



⑥

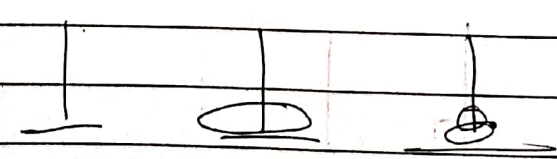
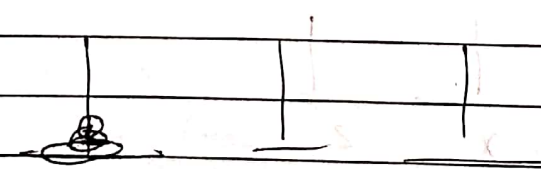


⑦



$n \text{ a } x \rightarrow y \quad z$

$n-1, x \rightarrow z, y \quad x \rightarrow y \quad n-1, z \rightarrow y, x$

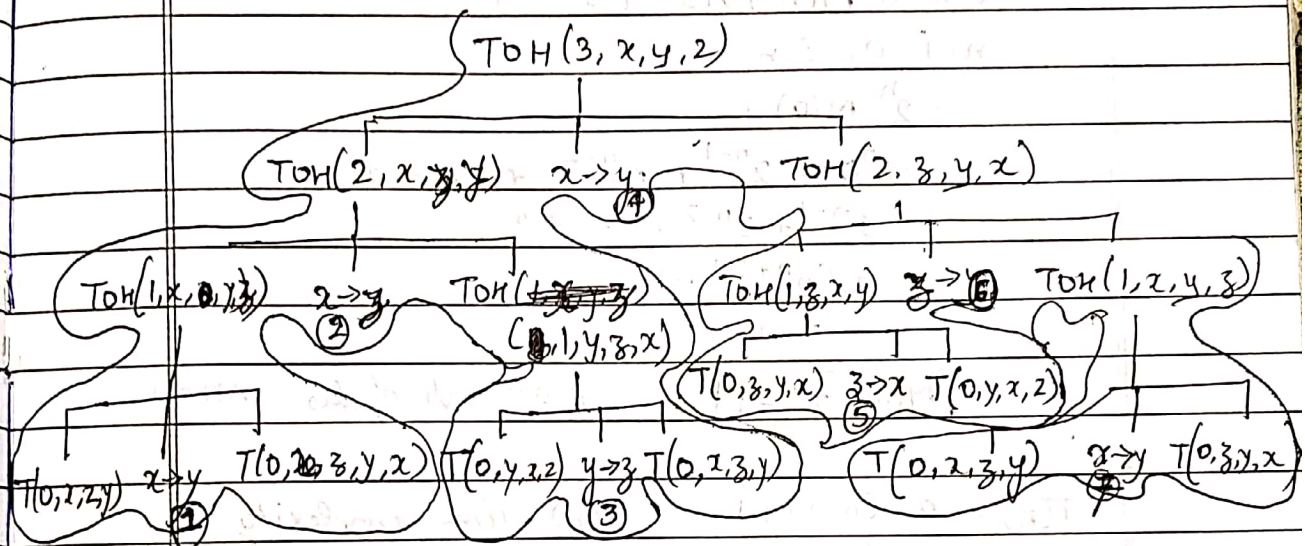


Algorithm for Towers of Hanoi

```

TOH(n, x, y, z)
{
    if (n > 1)
    {
        TOH(n-1, x, z, y)
        move top 'x' to y;
        TOH(n-1, z, y, x);
    }
}

```



→ 3 disc: No. of function invocations = 15
No. of movements = 7

Analysis of tower of hanoi

$TOH(n, x, y, z)$ $I(n) = 1 + 2I(n-1)$ — (1) $I(n)$ - Invocation required for n disc

$I(n) = 1, n=0$

$I(n-1) = 1 + 2I(n-2)$ — (2)

$I(n-2) = 1 + 2I(n-3)$ — (3)

$I(n) = 1 + 2(1 + 2I(n-2)) + 1$

$= 2^2 I(n-2) + 2 + 1$

$= 2^2 (2I(n-3) + 1) + 2 + 1$

$= 2^3 I(n-3) + 2^2 + 2 + 1$

$$= 2^i I(n-i) + 2^{i-1} + 2^{i-2} + \dots + 1$$

$$n-i=0, i=n$$

$$= 2^n I(0) + 2^{n-1} + 2^{n-2} + \dots + 1$$

$$= 2^n + 2^{n-1} + 2^{n-2} + \dots + 1$$

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

$$I(n) = 2^{n+1} - 1$$

$$n=3, I(n) = 2^4 - 1 = 15$$

$$M(n) = 1 + \frac{1}{2} M(n-1)$$

$$M(n) = 0, n=0 \quad \text{or} \quad M(n) = 1, n=1$$

$$M(n) = 2^i M(n-i) + 2^{i-1} + 2^{i-2} + \dots + 1$$

$$n-i=0, i=n$$

$$= 2^n M(0) +$$

$$= 2^n \cdot 0 + 2^{n-1} + 2^{n-2} + \dots + 1$$

$$= 2^{n-1} + 2^{n-2} + \dots + 1$$

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

$$M(n) = 2^n - 1$$

Movements of disc $M(n)$

$$T(n) = 2T(n-1) + 1 \quad \text{('} T(n) \text{' - Time complexity)}$$

$$T(n) = 1, n=0$$

$$T(n) = 2^{n+1} - 1 \quad (\text{same as } I(n))$$

$$T(n) = 2 \cdot 2^n - 1$$

$$T(n) = O(2^n)$$

$$T(n) = T(n-1) + 1$$

$$T(n)$$

$$T(n)$$

$$T(n)$$

$$\text{Stack Records} = (n+1) + 1 + (n) + 1 + \dots + 1$$

$$= O(n)$$

Improved algo

TOH(n, x, y, z)

{

if (n > 1)

{

TOH(n-1, x, z, y)

move top 'x' to 'y'

TOH(n-1, z, y, x)

}

else

if (n == 1) move 'x' to 'y'

$$I(n) = 2I(n-1) + 1$$

$$I(n) = 1, n = 1$$

$$I(n) = 1, n = 0$$

$$I(n) = 2^i I(n-i) + 2^{i-1} + 2^{i-2} + \dots + 1$$

$$n-i = 1$$

$$= i = n-1$$

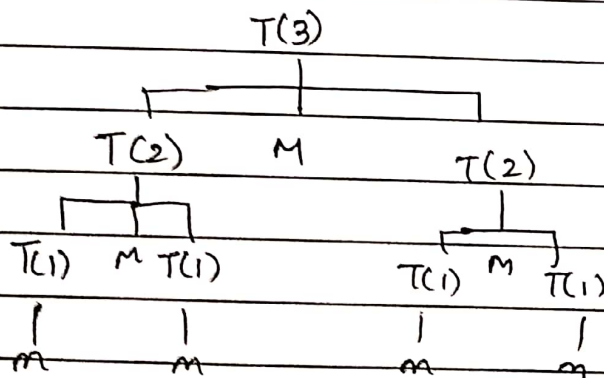
$$2^{n-1} \cdot 1 + 2^{n-2} + 2^{n-3} + \dots + 1$$

$$= 2^{n-1} + 2^{n-2} + \dots + 1$$

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

$$I(n) = 2^n - 1$$

$$n=3, I(n) = 2^3 - 1 = 7$$



No. of invocations = 7