

# UNIT 1 ANALYSIS OF ALGORITHMS

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## 1.0 INTRODUCTION

A common person's belief is that a computer can do anything. This is far from truth. In reality, computer can perform only certain predefined instructions. The formal representation of this model as a sequence of instructions is called an algorithm, and coded algorithm, in a specific computer language is called a program. Analysis of algorithms has been an area of research in computer science; evolution of very high speed computers has not diluted the need for the design of time-efficient algorithms.

Complexity theory in computer science is a part of theory of computation dealing with the resources required during computation to solve a given problem. The most common resources are *time* (how many steps (time) does it take to solve a problem) and *space* (how much memory does it take to solve a problem). It may be noted that complexity theory differs from computability theory, which deals with whether a problem can be solved or not through algorithms, regardless of the resources required.

Analysis of Algorithms is a field of computer science whose overall goal is understand the complexity of algorithms. While an extremely large amount of research work is devoted to the worst-case evaluations, the focus in these pages is methods for average-case. One can easily grasp that the focus has shifted from computer to computer programming and then to creation of an algorithm. This is algorithm design, heart of problem solving.

## 1.1 OBJECTIVES

After going through this unit, you should be able to:

- understand the concept of algorithm;
- understand the mathematical foundation underlying the analysis of algorithm;
- to understand various asymptotic notations, such as Big O notation, theta notation and omega (big O,  $\Theta$ ,  $\Omega$ ) for analysis of algorithms;
- understand various notations for defining the complexity of algorithm;
- define the complexity of various well known algorithms, and
- learn the method to calculate time complexity of algorithm.

## 1.2 MATHEMATICAL BACKGROUND

To analyse an algorithm is to determine the amount of resources (such as time and storage) that are utilized by to execute. Most algorithms are designed to work with inputs of arbitrary length.

Algorithm analysis is an important part of a broader computational complexity theory, which provides theoretical estimates for the resources needed by any algorithm which solves a given computational problem. These estimates provide an insight into reasonable directions of search for efficient algorithms.

### Definition of Algorithm

Algorithm should have the following five characteristic features:

1. Input
2. Output
3. Definiteness
4. Effectiveness
5. Termination.

Therefore, an algorithm can be defined as a sequence of definite and effective instructions, which terminates with the production of correct output from the given input.

### Complexity classes

All decision problems fall into sets of comparable complexity, called complexity classes.

The complexity class P is the set of decision problems that can be solved by a deterministic machine in polynomial time. This class corresponds to set of problems which can be effectively solved in the worst cases. We will consider algorithms belonging to this class for analysis of time complexity. Not all algorithms in these classes make practical sense as many of them have higher complexity. These are discussed later.

The complexity class NP is a set of decision problems that can be solved by a non-deterministic machine in polynomial time. This class contains many problems like Boolean satisfiability problem, Hamiltonian path problem and the Vertex cover problem.

### What is Complexity?

Complexity refers to the rate at which the required storage or consumed time grows as a function of the problem size. The absolute growth depends on the machine used to execute the program, the compiler used to construct the program, and many other factors. We would like to have a way of describing the inherent complexity of a program (or piece of a program), independent of machine/compiler considerations. This means that we must not try to describe the absolute time or storage needed. We must instead concentrate on a “proportionality” approach, expressing the complexity in terms of its relationship to some known function. This type of analysis is known as **asymptotic analysis**. It may be noted that we are dealing with complexity of an algorithm not that of a problem. For example, the simple problem could have high order of time complexity and vice-versa.

## Asymptotic Analysis

Asymptotic analysis is based on the idea that as the problem size grows, the complexity can be described as a simple proportionality to some known function. This idea is incorporated in the “Big O”, “Omega” and “Theta” notation for asymptotic performance.

The notations like “Little Oh” are similar in spirit to “Big Oh” ; but are rarely used in computer science for asymptotic analysis.

### Tradeoff between space and time complexity

We may sometimes seek a tradeoff between space and time complexity. For example, we may have to choose a data structure that requires a lot of storage in order to reduce the computation time. Therefore, the programmer must make a judicious choice from an informed point of view. The programmer must have some verifiable basis based on which a data structure or algorithm can be selected Complexity analysis provides such a basis.

We will learn about various techniques to bind the complexity function. In fact, our aim is not to count the exact number of steps of a program or the exact amount of time required for executing an algorithm. In theoretical analysis of algorithms, it is common to estimate their complexity in asymptotic sense, i.e., to estimate the complexity function for reasonably large length of input ‘n’. Big O notation, omega notation  $\Omega$  and theta notation  $\Theta$  are used for this purpose. In order to measure the performance of an algorithm underlying the computer program, our approach would be based on a concept called asymptotic measure of complexity of algorithm. There are notations like big O,  $\Theta$ ,  $\Omega$  for asymptotic measure of growth functions of algorithms. The most common being big-O notation. The asymptotic analysis of algorithms is often used because time taken to execute an algorithm varies with the input ‘n’ and other factors which may differ from computer to computer and from run to run. The essences of these asymptotic notations are to bind the growth function of time complexity with a function for sufficiently large input.

### The $\Theta$ -Notation (Tight Bound)

This notation bounds a function to within constant factors. We say  $f(n) = \Theta(g(n))$  if there exist positive constants  $n_0$ ,  $c_1$  and  $c_2$  such that to the right of  $n_0$  the value of  $f(n)$  always lies between  $c_1g(n)$  and  $c_2g(n)$ , both inclusive. The *Figure 1.1* gives an idea about function  $f(n)$  and  $g(n)$  where  $f(n) = \Theta(g(n))$ . We will say that the function  $g(n)$  is asymptotically tight bound for  $f(n)$ .

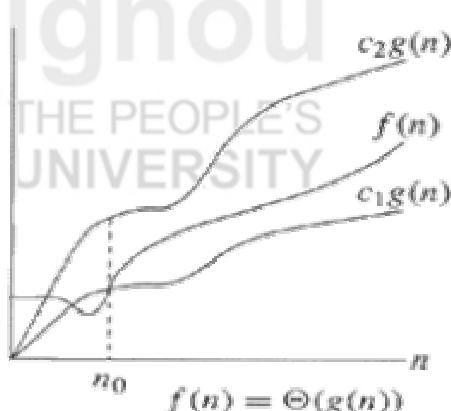


Figure 1.1 : Plot of  $f(n) = \Theta(g(n))$

For example, let us show that the function  $f(n) = \frac{1}{3}n^2 - 4n = \Theta(n^2)$ .

Now, we have to find three positive constants,  $c_1, c_2$  and  $n_0$  such that

$$c_1 n^2 \leq \frac{1}{3} n^2 - 4n \leq c_2 n^2 \text{ for all } n \geq n_0$$

$$\Rightarrow c_1 \leq \frac{1}{3} - \frac{4}{n} \leq c_2$$

By choosing  $n_0 = 1$  and  $c_2 \geq 1/3$  the right hand inequality holds true.

Similarly, by selecting  $n_0 = 13$   $c_1 \leq 1/39$ , the right hand inequality holds true. So, for  $c_1 = 1/39$ ,  $c_2 = 1/3$  and  $n_0 \geq 13$ , it follows that  $1/3 n^2 - 4n = \Theta(n^2)$ .

Certainly, there are other choices for  $c_1, c_2$  and  $n_0$ . Now we may show that the function  $f(n) = 6n^3 \neq \Theta(n^2)$ .

To prove this, let us assume that  $c_3$  and  $n_0$  exist such that  $6n^3 \leq c_3 n^2$  for  $n \geq n_0$ . But this fails for sufficiently large  $n$ . Therefore  $6n^3 \neq \Theta(n^2)$ .

### The big O notation (Upper Bound)

This notation gives an upper bound for a function to within a constant factor. Figure 1.2 shows the plot of  $f(n) = O(g(n))$  based on big O notation. We write  $f(n) = O(g(n))$  if there are positive constants  $n_0$  and  $c$  such that to the right of  $n_0$ , the value of  $f(n)$  always lies on or below  $cg(n)$ .

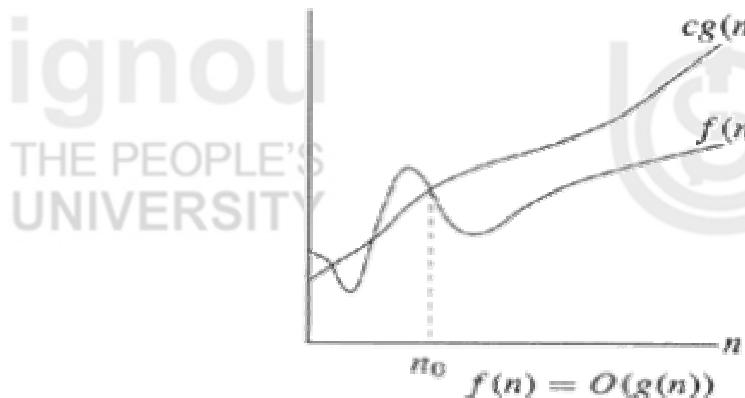


Figure 1.2: Plot of  $f(n) = O(g(n))$

Mathematically for a given function  $g(n)$ , we denote a set of functions by  $O(g(n))$  by the following notation:

$O(g(n)) = \{f(n) : \text{There exists a positive constant } c \text{ and } n_0 \text{ such that } 0 \leq f(n) \leq cg(n) \text{ for all } n \geq n_0\}$

Clearly, we use  $O$ -notation to define the upper bound on a function by using a constant factor  $c$ .

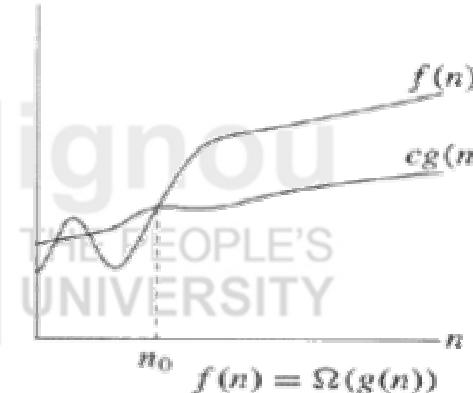
We can see from the earlier definition of  $\Theta$  that  $\Theta$  is a tighter notation than big- $O$  notation.

$f(n) = an + c$  is  $O(n)$  is also  $O(n^2)$ , but  $O(n)$  is asymptotically tight whereas  $O(n^2)$  is notation.

Whereas in terms of  $\Theta$  notation, the above function  $f(n)$  is  $\Theta(n)$ . As big- $O$  notation is upper bound of function, it is often used to describe the worst case running time of algorithms.

### The $\Omega$ -Notation (Lower Bound)

This notation gives a lower bound for a function to within a constant factor. We write  $f(n) = \Omega(g(n))$ , if there are positive constants  $n_0$  and  $c$  such that to the right of  $n_0$ , the value of  $f(n)$  always lies on or above  $cg(n)$ . *Figure 1.3* depicts the plot of  $f(n) = \Omega(g(n))$ .



**Figure 1.3: Plot of  $f(n) = \Omega(g(n))$**

Mathematically for a given function  $g(n)$ , we may define  $\Omega(g(n))$  as the set of functions.

$$\Omega(g(n)) = \{f(n) : \text{there exists a constant } c \text{ and } n_0 \geq 0 \text{ such that } 0 \leq cg(n) \leq f(n) \text{ for all } n \geq n_0\}.$$

Since  $\Omega$  notation describes lower bound, it is used to bound the best case running time of an algorithm.

## Asymptotic notation

Let us define a few functions in terms of above asymptotic notation.

$$\begin{aligned} \text{Example: } f(n) &= 3n^3 + 2n^2 + 4n + 3 \\ &= 3n^3 + 2n^2 + O(n), \text{ as } 4n + 3 \text{ is of } O(n) \\ &= 3n^3 + O(n^2), \text{ as } 2n^2 + O(n) \text{ is } O(n^2) \\ &= O(n^3) \end{aligned}$$

Example:  $f(n) = n^2 + 3n + 4$  is  $O(n^2)$ , since  $n^2 + 3n + 4 < 2n^2$  for all  $n > 10$ .

By definition of big- $O$ ,  $3n + 4$  is also  $O(n^2)$ , too, but as a convention, we use the tighter bound to the function, i.e.,  $O(n)$ .

Here are some rules about big- $O$  notation:

1.  $f(n) = O(f(n))$  for any function  $f$ . In other words, every function is bounded by itself.
2.  $a_k n^k + a_{k-1} n^{k-1} + \dots + a_1 n + a_0 = O(n^k)$  for all  $k \geq 0$  and for all  $a_0, a_1, \dots, a_k \in R$ . In other words, every polynomial of degree  $k$  can be bounded by the function  $n^k$ . Smaller order terms can be ignored in big- $O$  notation.
3. Basis of Logarithm can be ignored in big- $O$  notation i.e.  $\log_a n = O(\log_b n)$  for any bases  $a, b$ . We generally write  $O(\log n)$  to denote a logarithm n to any base.

4. Any logarithmic function can be bounded by a polynomial i.e.  $\log_b n = O(n^c)$  for any  $b$  (base of logarithm) and any positive exponent  $c > 0$ .
5. Any polynomial function can be bounded by an exponential function i.e.  $n^k = O(b^n)$ .
6. Any exponential function can be bound by the factorial function. For example,  $a^n = O(n!)$  for any base  $a$ .

### Check Your Progress 1

- 1) The function  $9n+12$  and  $1000n+400000$  are both  $O(n)$ .      True/False
- 2) If a function  $f(n) = O(g(n))$  and  $h(n) = O(g(n))$ , then  $f(n)+h(n) = O(g(n))$ .      True/False
- 3) If  $f(n) = n^2 + 3n$  and  $g(n) = 6000n + 34000$  then  $O(f(n)) < O(g(n))$ .      True/False
- 4) The asymptotic complexity of algorithms depends on hardware and other factors.      True/False
- 5) Give simplified *big-O* notation for the following growth functions:

- $30n^2$
- $10n^3 + 6n^2$
- $5n\log n + 30n$
- $\log n + 3n$
- $\log n + 32$

---

## 1.3 PROCESS OF ANALYSIS

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The objective analysis of an algorithm is to find its efficiency. Efficiency is dependent on the resources that are used by the algorithm. For example,

- CPU utilization (Time complexity)
- Memory utilization (Space complexity)
- Disk usage (I/O)
- Network usage (bandwidth).

There are two important attributes to analyse an algorithm. They are:

*Performance:* How much time/memory/disk/network bandwidth is actually used when a program is run. This depends on the algorithm, machine, compiler, etc.

*Complexity:* How do the resource requirements of a program or algorithm scale (the growth of resource requirements as a function of input). In other words, what happens to the performance of an algorithm, as the size of the problem being solved gets larger and larger? For example, the time and memory requirements of an algorithm which

computes the sum of 1000 numbers is larger than the algorithm which computes the sum of 2 numbers.

*Time Complexity:* The maximum time required by a *Turing machine* to execute on any input of length  $n$ .

*Space Complexity:* The amount of storage space required by an algorithm varies with the size of the problem being solved. The space complexity is normally expressed as an order of magnitude of the size of the problem, e.g.,  $O(n^2)$  means that if the size of the problem ( $n$ ) doubles then the working storage (memory) requirement will become four times.

### Determination of Time Complexity

#### *The RAM Model*

The random access model (RAM) of computation was devised by John von Neumann to study algorithms. Algorithms are studied in computer science because they are independent of machine and language.

We will do all our design and analysis of algorithms based on RAM model of computation:

- Each “simple” operation (+, -, =, if, call) takes exactly 1 step.
- Loops and subroutine calls are *not* simple operations, but depend upon the size of the data and the contents of a subroutine.
- Each memory access takes exactly 1 step.

The complexity of algorithms using big-O notation can be defined in the following way for a problem of size  $n$ :

- Constant-time method is “order 1”:  $O(1)$ . The time required is constant independent of the input size.
- Linear-time method is “order  $n$ ”:  $O(n)$ . The time required is proportional to the input size. If the input size doubles, then, the time to run the algorithm also doubles.
- Quadratic-time method is “order  $N$  squared”:  $O(n^2)$ . The time required is proportional to the square of the input size. If the input size doubles, then, the time required will increase by four times.

The process of analysis of algorithm (program) involves analyzing each step of the algorithm. It depends on the kinds of statements used in the program.

Consider the following example:

#### *Example 1: Simple sequence of statements*

Statement 1;

Statement 2;

...

...

Statement k;

The total time can be found out by adding the times for all statements:

$$\text{Total time} = \text{time(statement 1)} + \text{time(statement 2)} + \dots + \text{time(statement } k\text{)}.$$

It may be noted that time required by each statement will greatly vary depending on whether each statement is simple (involves only basic operations) or otherwise. Assuming that each of the above statements involve only basic operation, the time for each simple statement is constant and the total time is also constant:  $O(1)$ .

*Example 2: if-then-else statements*

In this example, assume the statements are simple unless noted otherwise.

if-then-else statements

```
if (cond) {  
    sequence of statements 1  
}  
else {  
    sequence of statements 2  
}
```

In this, if-else statement, either sequence 1 will execute, or sequence 2 will execute depending on the boolean condition. The worst-case time in this case is the slower of the two possibilities. For example, if sequence 1 is  $O(N^2)$  and sequence 2 is  $O(1)$ , then the worst-case time for the whole if-then-else statement would be  $O(N^2)$ .

*Example 3: for loop*

```
for (i = 0; i < n; i++) {  
    sequence of statements  
}
```

Here, the loop executes  $n$  times. So, the sequence of statements also executes  $n$  times. Since we assume the time complexity of the statements are  $O(1)$ , the total time for the loop is  $n * O(1)$ , which is  $O(n)$ . Here, the number of statements does not matter as it will increase the running time by a constant factor and the overall complexity will be same  $O(n)$ .

*Example 4:nested for loop*

```
for (i = 0; i < n; i++) {  
    for (j = 0; j < m; j++) {  
        sequence of statements  
    }  
}
```

Here, we observe that, the outer loop executes  $n$  times. Every time the outer loop executes, the inner loop executes  $m$  times. As a result of this, statements in the inner loop execute a total of  $n * m$  times. Thus, the time complexity is  $O(n * m)$ . If we modify the conditional variables, where the condition of the inner loop is  $j < n$  instead of  $j < m$  (i.e., the inner loop also executes  $n$  times), then the total complexity for the nested loop is  $O(n^2)$ .

Example 4: Now, consider a function that calculates partial sum of an integer  $n$ .

```
int psum(int n)  
{  
    int i, partial_sum;
```

```

partial_sum = 0;           /* Line 1 */
for (i = 1; i <= n; i++) { /* Line 2 */
    partial_sum = partial_sum + i*i; /* Line 3 */
}
return partial_sum;        /* Line 4 */
}

```

This function returns the sum from  $i = 1$  to  $n$  of  $i$  squared, i.e.  $\text{psum} = 1^2 + 2^2 + 3^2 + \dots + n^2$ . As we have to determine the running time for each statement in this program, we have to count the number of statements that are executed in this procedure. The code at line 1 and line 4 are one statement each. The **for loop** on line 2 are actually  $2n+2$  statements:

- $i = 1$ ; statement : simple assignment, hence one statement.
- $i \leq n$ ; statement is executed once for each value of  $i$  from 1 to  $n+1$  (till the condition becomes false). The statement is executed  $n+1$  times.
- $i++$  is executed once for each execution of the body of the loop. This is executed  $n$  times.

Thus, the sum is  $1 + (n+1) + n+1 = 2n+3$  times.

In terms of big-O notation defined above, this function is  $O(n)$ , because if we choose  $c=3$ , then we see that  $cn > 2n+3$ . As we have already noted earlier, big-O notation only provides an upper bound to the function, it is also  $O(n\log(n))$  and  $O(n^2)$ , since  $n^2 > n\log(n) > 2n+3$ . However, we will choose the smallest function that describes the order of the function and it is  $O(n)$ .

By looking at the definition of Omega notation and Theta notation, it is also clear that it is of  $\Theta(n)$ , and therefore  $\Omega(n)$  too. Because if we choose  $c=1$ , then we see that  $cn < 2n+3$ , hence  $\Omega(n)$ . Since  $2n+3 = O(n)$ , and  $2n+3 = \Omega(n)$ , it implies that  $2n+3 = \Theta(n)$ , too.

It is again reiterated here that smaller order terms and constants may be ignored while describing asymptotic notation. For example, if  $f(n) = 4n+6$  instead of  $f(n) = 2n+3$  in terms of big-O,  $\Omega$  and  $\Theta$ , this does not change the order of the function. The function  $f(n) = 4n+6 = O(n)$  (by choosing  $c$  appropriately as 5);  $4n+6 = \Omega(n)$  (by choosing  $c = 1$ ), and therefore  $4n+6 = \Theta(n)$ . The essence of this analysis is that in these asymptotic notation, we can count a statement as one, and should not worry about their relative execution time which may depend on several hardware and other implementation factors, as long as it is of the order of 1, i.e.  $O(1)$ .

#### *Exact analysis of insertion sort:*

Let us consider the following pseudocode to analyse the exact runtime complexity of insertion sort.

<u>Line</u>	<u>Pseudocode</u>	<u>Cost factor</u>	<u>No. of iterations</u>
1	For $j=2$ to length [A] do	$c_1$	$(n-1) + 1$
2	{ key = A[j]	$c_2$	$(n-1)$
3	$i = j - 1$	$c_3$	$(n-1)$
4	while ( $i > 0$ ) and ( $A[i] > \text{key}$ ) do	$c_4$	$\sum_{j=2}^n T_j$
5	$A[i+1] = A[I]$	$c_4$	$\sum_{j=2}^n T_j - 1$

6                    $i = I - 1 \}$

$c5$

7                    $A[I+I] = \text{key } \}$

$c6$

$$\sum_{j=2}^n T_j - 1$$

$n-1$

$T_j$  is the time taken to execute the statement during  $j^{th}$  iteration.

The statement at line 4 will execute  $T_j$  number of times.

The statements at lines 5 and 6 will execute  $T_j - 1$  number of times (one step less) each

Line 7 will execute  $(n-1)$  times

So, total time is the sum of time taken for each line multiplied by their cost factor.

$$T(n) = c1n + c2(n-1) + c3(n-1) + c4 \sum_{j=2}^n T_j + c5 \sum_{j=2}^n T_j - 1 + c6 \sum_{j=2}^n T_j - 1 + c7(n-1)$$

Three cases can emerge depending on the initial configuration of the input list. First, the case is where the list was already sorted, second case is the case wherein the list is sorted in reverse order and third case is the case where in the list is in random order (unsorted). The best case scenario will emerge when the list is already sorted.

*Worst Case:* Worst case running time is an upper bound for running time with any input. It guarantees that, irrespective of the type of input, the algorithm will not take any longer than the worst case time.

*Best Case :* It guarantees that under any circumstances the running time of algorithms will at least take this much time.

*Average case :* This gives the average running time of algorithm. The running time for any given size of input will be the average number of operations over all problem instances for a given size.

*Best Case :* If the list is already sorted then  $A[i] \leq \text{key}$  at line 4. So, rest of the lines in the inner loop will not execute. Then,

$T(n) = c1n + c2(n-1) + c3(n-1) + c4(n-1) = O(n)$ , which indicates that the time complexity is linear.

*Worst Case:* This case arises when the list is sorted in reverse order. So, the boolean condition at line 4 will be true for execution of line 1.

So, step line 4 is executed  $\sum_{j=2}^n j = n(n+1)/2 - 1$  times

$$\begin{aligned} T(n) &= c1n + c2(n-1) + c3(n-1) + c4(n(n+1)/2 - 1) + c5(n(n-1)/2) + c6(n(n-1)/2) \\ &+ c7(n-1) \\ &= O(n^2). \end{aligned}$$

*Average case :* In most of the cases, the list will be in some random order. That is, it neither sorted in ascending or descending order and the time complexity will lie somewhere between the best and the worst case.

$$T(n)_{\text{best}} < T(n)_{\text{Avg}} < T(n)_{\text{worst}}$$

Figure 1.4 depicts the best, average and worst case run time complexities of algorithms.

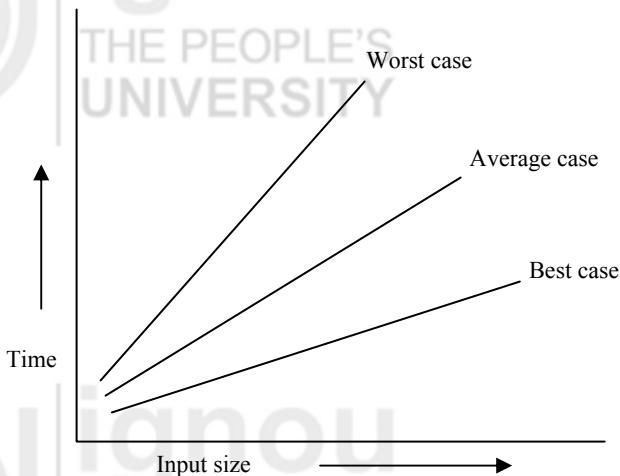


Figure 1.4 : Best, Average and Worst case scenarios

### ☛ Check Your Progress 2

- 1) The set of algorithms whose order is  $O(1)$  would run in the same time. True/False
- 2) Find the complexity of the following program in big O notation:

```
printMultiplicationTable(int max){  
    for(int i = 1; i <= max ; i ++)  
    {  
        for(int j = 1 ;j <= max ;j ++)  
            cout << (i * j) << " "  
            cout << endl ;  
    } //for
```

- 3) Consider the following program segment:

```
for (i = 1; i <= n; i *= 2)  
{  
    j = I;  
}
```

What is the running time of the above program segment in big O notation?

- 4) Prove that if  $f(n) = n^2 + 2n + 5$  and  $g(n) = n^2$  then  $f(n) = O(g(n))$ .
- 5) How many times does the following **for loop** will run

```
for (i=I; i<= n; i*2)  
    k = k + 1;  
end;
```

---

## 1.4 CALCULATION OF STORAGE COMPLEXITY

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As memory is becoming more and more cheaper, the prominence of runtime complexity is increasing. However, it is very much important to analyse the amount of memory used by a program. If the running time of algorithms is not good then it will

take longer to execute. But, if it takes more memory (the space complexity is more) beyond the capacity of the machine then the program will not execute at all. It is therefore more critical than run time complexity. But, the matter of respite is that memory is reutilized during the course of program execution.

We will analyse this for recursive and iterative programs.

For an iterative program, it is usually just a matter of looking at the variable declarations and storage allocation calls, e.g., number of variables, length of an array etc.

The analysis of recursive program with respect to space complexity is more complicated as the space used at any time is the total space used by all recursive calls active at that time.

Each recursive call takes a constant amount of space and some space for local variables and function arguments, and also some space is allocated for remembering where each call should return to. General recursive calls use linear space. That is, for  $n$  recursive calls, the space complexity is  $O(n)$ .

Consider the following example: *Binary Recursion* (A binary-recursive routine (potentially) calls itself twice).

1. If  $n$  equals 0 or 1, then return 1
2. Recursively calculate  $f(n-1)$
3. Recursively calculate  $f(n-2)$
4. Return the sum of the results from steps 2 and 3.

Time Complexity:  $O(\exp n)$

Space Complexity:  $O(\exp n)$

**Example:** Find the greatest common divisor (GCD) of two integers,  $m$  and  $n$ .  
The algorithm for GCD may be defined as follows:

While  $m$  is greater than zero:  
If  $n$  is greater than  $m$ , swap  $m$  and  $n$ .  
Subtract  $n$  from  $m$ .  
 $n$  is the GCD

#### Code in C

```
int gcd(int m, int n)
/* The precondition are : m>0 and n>0. Let g = gcd(m,n). */
{ while( m > 0 )
{
    if( n > m )
        { int t = m; m = n; n = t; } /* swap m and n*/
    /* m >= n > 0 */
    m -= n;
}
return n;
}
```

The space-complexity of the above algorithm is a constant. It just requires space for three integers  $m$ ,  $n$  and  $t$ . So, the space complexity is  $O(1)$ .

The time complexity depends on the loop and on the condition whether  $m > n$  or not. The real issue is, how many iterations take place? The answer depends on both  $m$  and  $n$ .

Best case: If  $m = n$ , then there is just one iteration.  $O(1)$

Worst case : If  $n = 1$ , then there are  $m$  iterations; this is the worst-case (also equivalently, if  $m = 1$  there are  $n$  iterations)  $O(n)$ .

The *space complexity* of a computer program is the amount of memory required for its proper execution. The important concept behind space required is that unlike time, space can be reused during the execution of the program. As discussed, there is often a trade-off between the time and space required to run a program.

In formal definition, the space complexity is defined as follows:

*Space complexity* of a Turing Machine: The (worst case) maximum length of the tape required to process an input string of length  $n$ .

In complexity theory, the class *PSPACE* is the set of decision problems that can be solved by a Turing machine using a polynomial amount of memory, and unlimited time.

### ☛ Check Your Progress 3

- 1) Why space complexity is more critical than time complexity?
- .....
- .....

- 2) What is the space complexity of Euclid Algorithm?
- .....
- .....

---

## 1.5 CALCULATION OF TIME COMPLEXITY

---

**Example 1:** Consider the following code :

$$x = 4y + 3$$

$$z = z + 1$$

$$p = 1$$

As we have seen,  $x$ ,  $y$ ,  $z$  and  $p$  are all scalar variables and the running time is constant irrespective of the value of  $x, y, z$  and  $p$ . Here, we emphasize that each line of code may take different time, to execute, but the bottom line is that they will take constant amount of time. Thus, we will describe run time of each line of code as  $O(1)$ .

**Example 2: Binary search**

Binary search in a sorted list is carried out by dividing the list into two parts based on the comparison of the key. As the search interval halves each time, the iteration takes place in the search. The search interval will look like following after each iteration  $N, N/2, N/4, N/8, \dots, 8, 4, 2, 1$

The number of iterations (number of elements in the series) is not so evident from the above series. But, if we take logs of each element of the series, then

$$\log_2 N, \log_2 N - 1, \log_2 N - 2, \log_2 N - 3, \dots, 3, 2, 1, 0$$

As the sequence decrements by 1 each time the total elements in the above series are  $\log_2 N + 1$ . So, the number of iterations is  $\log_2 N + 1$  which is of the order of  $O(\log_2 N)$ .

### Example 3: Travelling Salesman problem

Given: n connected cities and distances between them

Find: tour of minimum length that visits every city.

Solutions: How many tours are possible?

$$n * (n - 1) \dots * 1 = n!$$

Because  $n! > 2^{(n-1)}$

So  $n! = \Omega(2^n)$  (lower bound)

As of now, there is no algorithm that finds a tour of minimum length as well as covers all the cities in polynomial time. However, there are numerous very good heuristic algorithms.

*The complexity Ladder:*

- $T(n) = O(1)$ . This is called constant growth.  $T(n)$  does not grow at all as a function of  $n$ , it is a constant. For example, array access has this characteristic.  $A[i]$  takes the same time independent of the size of the array  $A$ .
- $T(n) = O(\log_2(n))$ . This is called logarithmic growth.  $T(n)$  grows proportional to the base 2 logarithm of  $n$ . Actually, the base of logarithm does not matter. For example, binary search has this characteristic.
- $T(n) = O(n)$ . This is called linear growth.  $T(n)$  grows linearly with  $n$ . For example, looping over all the elements in a one-dimensional array of  $n$  elements would be of the order of  $O(n)$ .
- $T(n) = O(n \log(n))$ . This is called **nlogn** growth.  $T(n)$  grows proportional to  $n$  times the base 2 logarithm of  $n$ . Time complexity of Merge Sort has this characteristic. In fact, no sorting algorithm that uses comparison between elements can be faster than  $n \log n$ .
- $T(n) = O(n^k)$ . This is called polynomial growth.  $T(n)$  grows proportional to the  $k$ -th power of  $n$ . We rarely consider algorithms that run in time  $O(n^k)$  where  $k$  is bigger than 2, because such algorithms are very slow and not practical. For example, selection sort is an  $O(n^2)$  algorithm.
- $T(n) = O(2^n)$ . This is called exponential growth.  $T(n)$  grows exponentially. Exponential growth is the most-danger growth pattern in computer science. Algorithms that grow this way are basically useless for anything except for very small input size.

Table 1.1 compares various algorithms in terms of their complexities.

Table 1.2 compares the typical running time of algorithms of different orders.

The growth patterns above have been listed in order of increasing size.

That is,  $O(1) < O(\log(n)) < O(n \log(n)) < O(n^2) < O(n^3), \dots, O(2^n)$ .

Notation	Name	Example
$O(1)$	Constant	Constant growth. Does

		not grow as a function of n. For example, accessing array for one element A[i]
$O(\log n)$	Logarithmic	Binary search
$O(n)$	Linear	Looping over n elements, of an array of size n (normally).
$O(n \log n)$	Sometimes called “linearithmic”	Merge sort
$O(n^2)$	Quadratic	Worst time case for insertion sort, matrix multiplication
$O(n^c)$	Polynomial, sometimes “geometric”	
$O(c^n)$	Exponential	
$O(n!)$	Factorial	

Table 1.1 : Comparison of various algorithms and their complexities

Array size	Logarithmic: $\log_2 N$	Linear: N	Quadratic: $N^2$	Exponential: $2^N$
8	3	8	64	256
128	7	128	16,384	$3.4 \times 10^{38}$
256	8	256	65,536	$1.15 \times 10^{77}$
1000	10	1000	1 million	$1.07 \times 10^{301}$
100,000	17	100,000	10 billion	.....

Table 1.2: Comparison of typical running time of algorithms of different orders

## 1.6 SUMMARY

Computational complexity of algorithms are generally referred to by space complexity (space required for running program) and time complexity (time required for running the program). In the field of computer science, the concept of runtime complexity has been studied vigorously. Enough research is being carried out to find more efficient algorithms for existing problems. We studied various asymptotic notation, to describe the time complexity and space complexity of algorithms, namely the *big-O*, *Omega* and *Theta* notations. These asymptotic orders of time and space complexity describe how best or worst an algorithm is for a sufficiently large input.

We studied about the process of calculation of runtime complexity of various algorithms. The exact analysis of insertion sort was discussed to describe the best case, worst case and average case scenario.

## 1.7 SOLUTIONS / ANSWERS

### Check Your Progress 1

- 1) True

- 2) True  
3) False  
4) False  
5)  $O(n^2)$ ,  $O(n^3)$ ,  $O(n \log n)$ ,  $O(\log n)$ ,  $O(\log \log n)$

### Check Your Progress 2

- 1) True  
2)  $O(\max * (2 * \max)) = O(2 * \max * \max) = O(2 * n * n) = O(2n^2) = O(n^2)$   
3)  $O(\log(n))$   
5)  $\log n$

### Check Your Progress 3

- 1) If the running time of algorithms is not good, then it will take longer to execute. But, if it takes more memory (the space complexity is more) beyond the capacity of the machine then the program will not execute.  
2)  $O(1)$ .

---

## 1.8 FURTHER READINGS

---

1. *Fundamentals of Data Structures in C++*; E.Horowitz, Sahni and D.Mehta; Galgotia Publications.
2. *Data Structures and Program Design in C*; Kruse, C.L.Tonodo and B.Leung; Pearson Education.

#### Reference Websites

- [http://en.wikipedia.org/wiki/Big\\_O\\_notation](http://en.wikipedia.org/wiki/Big_O_notation)  
<http://www.webopedia.com>

## UNIT 2 ARRAYS

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## 2.0 INTRODUCTION

This unit introduces a data structure called Arrays. The simplest form of array is a one-dimensional array that may be defined as a finite ordered set of homogeneous elements, which is stored in contiguous memory locations. For example, an array may contain all integers or all characters or any other data type, but may not contain a mix of data types.

The general form for declaring a single dimensional array is:

```
data_type array_name[expression];
```

where data\_type represents data type of the array. That is, integer, char, float etc. array\_name is the name of array and expression which indicates the number of elements in the array.

For example, consider the following C declaration:

```
int a[100];
```

It declares an array of 100 integers.

The amount of storage required to hold an array is directly related to its type and size. For a single dimension array, the total size in bytes required for the array is computed as shown below.

Memory required (in bytes) = size of (data type) X length of array

The first array index value is referred to as its lower bound and in C it is always 0 and the maximum index value is called its upper bound. The number of elements in the array, called its range is given by upper bound-lower bound.

We store values in the arrays during program execution. Let us now see the process of initializing an array while declaring it.

```
int a[4] = {34,60,93,2};  
int b[] = {2,3,4,5};  
float c[] = {-4.6,81,- 60};
```

We conclude the following facts from these examples:

- (i) If the array is initialized at the time of declaration, then the dimension of the array is optional.
- (ii) Till the array elements are not given any specific values, they contain garbage values.

## 2.1 OBJECTIVES

After going through this unit, you will be able to:

- use Arrays as a proper data structure in programs;
- know the advantages and disadvantages of Arrays;
- use multidimensional arrays, and
- know the representation of Arrays in memory.

## 2.2 ARRAYS AND POINTERS

C compiler does not check the bounds of arrays. It is your job to do the necessary work for checking boundaries wherever needed.

One of the most common arrays is a string, which is simply an array of characters terminated by a null character. The value of the null character is zero. A string constant is a one-dimensional array of characters terminated by a null character(0).

For example, consider the following:

```
char message[ ]= {'e', 'x', 'a', 'm', 'p', 'l','e','\0'};
```

Also, consider the following string which is stored in an array:

“sentence\n”

Figure 2.1 shows the way a character array is stored in memory. Each character in the array occupies one byte of memory and the last character is always ‘0’. Note that ‘0’ and ‘0’ are not the same. The elements of the character array are stored in contiguous memory locations.

s	e	n	t	e	n	c	e	\n	\0
---	---	---	---	---	---	---	---	----	----

Figure 2.1: String in Memory

C concedes a fact that the user would use strings very often and hence provides a short cut for initialization of strings.

For example, the string used above can also be initialized as

```
char name[ ] = “sentence\n”;
```

Note that, in this declaration ‘0’ is not necessary. C inserts the null character automatically.

Multidimensional arrays are defined in the same manner as one-dimensional arrays, except that a separate pair of square brackets is required for each subscript. Thus a two-dimensional array will require two pairs of square brackets, a three-dimensional array will require three pairs of square brackets and so on.

The format of declaration of a multidimensional array in C is given below:

`data_type array_name [expr 1] [expr 2] .... [expr n];`

where `data_type` is the type of array such as `int`, `char` etc., `array_name` is the name of array and `expr 1`, `expr 2`, ..., `expr n` are positive valued integer expressions.

The schematic of a two-dimensional array of size  $3 \times 5$  is shown in *Figure 2.2*.

Row 0	→	a[0][0]	a[0][1]	a[0][2]	a[0][3]	A[0][4]
Row 1	→	a[1][0]	a[1][1]	a[1][2]	a[1][3]	A[1][4]
Row 3	→	a[2][0]	a[2][1]	a[2][2]	a[2][3]	A[2][4]

**Figure 2.2: Schematic of a Two-Dimensional Array**

In the case of a two-dimensional array, the following formula yields the number of bytes of memory needed to hold it:

$$\text{bytes} = \text{size of } 1^{\text{st}} \text{ index} \times \text{size of } 2^{\text{nd}} \text{ index} \times \text{size of (base type)}$$

The pointers and arrays are closely related. As you know, an array name without an index is a pointer to the first element in the array.

Consider the following array:

```
char p[10];
```

`p` and `&p[0]` are identical because the address of the first element of an array is the same as the address of the array. So, an array name without an index generates a pointer. Conversely a pointer can be indexed as if it were declared to be an array.

For example, consider the following program fragment:

```
int *x, a [10];
x = a;
x[5] = 100;
*(x+5) = 100;
```

Both assignment statements place the value 100 in the sixth element of `a`. Furthermore the  $(0,4)$  element of a two-dimensional array may be referenced in the following two ways: either by array indexing `a[0][4]`, or by the pointer `*((int *) a+4)`.

In general, for any two-dimensional array `a[j][k]` is equivalent to:

`*((base type *)a + (j * rowlength)*k)`

## 2.3 SPARSE MATRICES

Matrices with good number of zero entries are called sparse matrices.

Consider the following matrices of *Figure 2.3*.

$$\begin{bmatrix} 4 & & & & \\ 3 & -5 & & & \\ 1 & 0 & 6 & & \\ -7 & 8 & -1 & 3 & \\ 5 & -2 & 0 & 2 & -8 \end{bmatrix}$$

$$\begin{bmatrix} 5 & -3 & & & \\ 1 & 4 & 3 & & \\ 9 & -3 & 6 & & \\ & 2 & 4 & -7 & \\ & 3 & -1 & 0 & \\ & 6 & -5 & 8 & \\ & 3 & -1 & & \end{bmatrix}$$

(a)

(b)

**Figure 2.3: (a) Triangular Matrix (b) Tridiagonal Matrix**

A triangular matrix is a square matrix in which all the elements either above or below the main diagonal are zero. Triangular matrices are sparse matrices. A tridiagonal matrix is a square matrix in which all the elements except for the main diagonal, diagonals on the immediate upper and lower side are zeroes. Tridiagonal matrices are also sparse matrices.

Let us consider a sparse matrix from storage point of view. Suppose that the entire sparse matrix is stored. Then, a considerable amount of memory which stores the matrix consists of zeroes. This is nothing but wastage of memory. In real life applications, such wastage may count to megabytes. So, an efficient method of storing sparse matrices has to be looked into.

*Figure 2.4* shows a sparse matrix of order  $7 \times 6$ .

	0	1	2	3	4	5
0	0	0	0	5	0	0
1	0	4	0	0	0	0
2	0	0	0	0	9	0
3	0	3	0	2	0	0
4	1	0	2	0	0	0
5	0	0	0	0	0	0
6	0	0	8	0	0	0

**Figure 2.4: Representation of a sparse matrix of order  $7 \times 6$**

A common way of representing non zero elements of a sparse matrix is the 3-tuple form. The first row of sparse matrix always specifies the number of rows, number of columns and number of non zero elements in the matrix. The number 7 represents the total number of rows sparse matrix. Similarly, the number 6 represents the total number of columns in the matrix. The number 8 represents the total number of non zero elements in the matrix. Each non zero element is stored from the second row, with the 1<sup>st</sup> and 2<sup>nd</sup> elements of the row, indicating the row number and column number respectively in which the element is present in the original matrix. The 3<sup>rd</sup> element in this row stores the actual value of the non zero element. For example, the 3-tuple representation of the matrix of *Figure 2.4* is shown in *Figure 2.5*.

7,	7,	9
0,	3,	5
1,	1,	4
2,	4,	9
3,	1,	3
3,	3,	2
4,	0,	1
4,	2,	2
6,	2,	8

Figure 2.5: 3-tuple representation of Figure 2.4

The following program 1.1 accepts a matrix as input, which is sparse and prints the corresponding 3-tuple representations.

### Program 1.1

```
/* The program accepts a matrix as input and prints the 3-tuple representation
of it*/
```

```
#include<stdio.h>

void main()
{
    int a[5][5],rows,columns,i,j;

    printf("enter the order of the matrix. The order should be less than 5 × 5:\n");
    scanf("%d %d",&rows,&columns);
    printf("Enter the elements of the matrix:\n");

    for(i=0;i<rows;i++)
        for(j=0;j<columns;j++)
    {
        { scanf("%d",&a[i][j]);
        }
        printf("The 3-tuple representation of the matrix is:\n");

        for(i=0;i<rows;i++)
            for(j=0;j<columns;j++)
        {
            if (a[i][j]!=0)
            {
                printf("%d %d %d\n", (i+1),(j+1),a[i][j]);
            }
        }
    }
}
```

### Output:

enter the order of the matrix. The order should be less than  $5 \times 5$ :

3 3

Enter the elements of the matrix:

1 2 3

0 1 0

0 0 4

The 3-tuple representation of the matrix is:

1	1	1
1	2	2
1	3	3
2	2	1
3	3	4

The program initially prompted for the order of the input matrix with a warning that the order should not be greater than  $5 \times 5$ . After accepting the order, it prompts for the elements of the matrix. After accepting the matrix, it checks each element of the matrix for a non zero. If the element is non zero, then it prints the row number and column number of that element along with its value.

### Check Your Progress 1

- 1) If the array is \_\_\_\_\_ at the time of declaration, then the dimension of the array is optional.
- 2) A sparse matrix is a matrix which is having good number of \_\_\_\_\_ elements.
- 3) At maximum, an array can be a two-dimensional array. True/False

## 2.4 POLYNOMIALS

Polynomials like  $5x^4 + 2x^3 + 7x^2 + 10x - 8$  can be represented using arrays. Arithmetic operations like addition and multiplication of polynomials are common and most often, we need to write a program to implement these operations.

The simplest way to represent a polynomial of degree ‘ $n$ ’ is to store the coefficient of  $(n+1)$  terms of the polynomial in an array. To achieve this, each element of the array should consist of two values, namely, coefficient and exponent. While maintaining the polynomial, it is assumed that the exponent of each successive term is less than that of the previous term. Once we build an array to represent a polynomial, we can use such an array to perform common polynomial operations like addition and multiplication.

Program 1.2 accepts two polynomials as input and adds them.

#### Program 1.2

*/\* The program accepts two polynomials as input and prints the resultant polynomial due to the addition of input polynomials \*/*

```
#include<stdio.h>

void main()
{
    int poly1[6][2],poly2[6][2],term1,term2,match,proceed,i,j;

    printf("Enter the number of terms in the first polynomial. They should be less
than 6:\n");
    scanf("%d",&term1);
    printf("Enter the number of terms in the second polynomial. They should be
less than 6:\n");
    scanf("%d",&term2);
    printf("Enter the coefficient and exponent of each term of the first
polynomial:\n");
    for(i=0;i<term1;i++)
    {scanf("%d %d",&poly1[i][0],&poly1[i][1]);
    }

    printf("Enter the coefficient and exponent of each term of the second
polynomial:\n");
    for(i=0;i<term2;i++)
    {scanf("%d %d",&poly2[i][0],&poly2[i][1]);}
```

```

    }
printf("The resultant polynomial due to the addition of the input two
polynomials:\n");

```

```

for(i=0;i<term1;i++)
{
    match=0;
    for(j=0;j<term2;j++)
        {
            if (match==0)

                if(poly1[i][1]==poly2[j][1])
                    { printf("%d %d\n",(poly1[i][0]+poly2[j][0]), poly1[i][1]);
                      match=1;
                    }
            }

        }

for(i=0;i<term1;i++)
{ proceed=1;

    for(j=0;j<term2;j++)
        {
            if(proceed==1)
                if(poly1[i][1]!=poly2[j][1])
                    proceed=1;
                else
                    proceed=0;
            }

        }

    if(proceed==1)
        printf("%d %d\n",poly1[i][0],poly1[i][1]);
}

for(i=0;i<term2;i++)
{ proceed=1;

    for(j=0;j<term1;j++)
        {
            if(proceed==1)
                if(poly2[i][1]!=poly1[j][1])
                    proceed=1;
                else
                    proceed=0;
            }

        }

    if(proceed==1)
        printf("%d %d",poly2[i][0],poly2[i][1]);
}
}

```

### **Output:**

Enter the number of terms in the first polynomial. They should be less than 6 : 5.

Enter the number of terms in the second polynomial. They should be less than 6 : 4.

Enter the coefficient and exponent of each term of the first polynomial:

1 2  
2 4  
3 6

Enter the coefficient and exponent of each term of the second polynomial:

The resultant polynomial due to the addition of the input two polynomials:

The program initially prompted for the number of terms of the two polynomials. Then, it prompted for the entry of the terms of the two polynomials one after another. Initially, it adds the coefficients of the corresponding terms of both the polynomials whose exponents are the same. Then, it prints the terms of the first polynomial who does not have corresponding terms in the second polynomial with the same exponent. Finally, it prints the terms of the second polynomial who does not have corresponding terms in the first polynomial.

## 2.5 REPRESENTATION OF ARRAYS

It is not uncommon to find a large number of programs which process the elements of an array in sequence. But, does it mean that the elements of an array are also stored in sequence in memory. The answer depends on the operating system under which the program is running. However, the elements of an array are stored in sequence to the extent possible. If they are being stored in sequence, then how are they sequenced. Is it that the elements are stored row wise or column wise? Again, it depends on the operating system. The former is called row major order and the later is called column major order.

### 2.5.1 Row Major Representation

The first method of representing a two-dimensional array in memory is the row major representation. Under this representation, the first row of the array occupies the first set of the memory location reserved for the array, the second row occupies the next set, and so forth.

The schematic of row major representation of an Array is shown in *Figure 2.6*. Let us consider the following two-dimensional array:

a	b	c	d
e	f	g	h
i	j	k	l

To make its equivalent row major representation, we perform the following process:

Move the elements of the second row starting from the first element to the memory location adjacent to the last element of the first row. When this step is applied to all the rows except for the first row, you have a single row of elements. This is the Row major representation.

By application of above mentioned process, we get {a, b, c, d, e, f, g, h, i, j, k, l }

Row 0	Row 1	Row 2	.....	Row i		
-------	-------	-------	-------	-------	--	--

Figure 2.6: Schematic of a Row major representation of an Array

### 2.5.2 Column Major Representation

The second method of representing a two-dimensional array in memory is the column major representation. Under this representation, the first column of the array occupies the first set of the memory locations reserved for the array. The second column occupies the next set and so forth. The schematic of a column major representation is shown in *Figure 2.7*.

Consider the following two-dimensional array:

a	b	c	d
e	f	g	h
i	j	k	l

To make its equivalent column major representation, we perform the following process:

Transpose the elements of the array. Then, the representation will be same as that of the row major representation.

By application of above mentioned process, we get {a, e, i, b, f, j, c, g, k, d, h, l}

Col 0	Col 1	Col 2	.....	Col i		
-------	-------	-------	-------	-------	--	--

Figure 2.7: Schematic of a Column major representation of an Array

### Check Your Progress 2

- 1) An array can be stored either \_\_\_\_\_ or \_\_\_\_\_.
- 2) In \_\_\_\_\_, the elements of array are stored row wise.
- 3) In \_\_\_\_\_, the elements of array are stored column wise.

## 2.6 APPLICATIONS

Arrays are simple, but reliable to use in more situations than you can count. Arrays are used in those problems when the number of items to be solved is fixed. They are easy to traverse, search and sort. It is very easy to manipulate an array rather than other subsequent data structures. Arrays are used in those situations where the size of array can be established before hand. Also, they are used in situations where the insertions and deletions are minimal or not present. Insertion and deletion operations will lead to wastage of memory or will increase the time complexity of the program due to the reshuffling of elements.

## 2.7 SUMMARY

In this unit, we discussed the data structure **arrays** from the application point of view and representation point of view. Two applications namely representation of a sparse matrix in a 3-tuple form and addition of two polynomials are given in the form of programs. The format for declaration and utility of both single and two-dimensional arrays are covered. Finally, the most important issue of representation was discussed. As part of it, row major and column major orders are discussed.

## 2.8 SOLUTIONS / ANSWERS

### Check Your Progress 1

- 1) Initialized
- 2) Zero
- 3) False

### Check Your Progress 2

- 1) Row wise, column wise
- 2) Row major representation
- 3) Column major representation

## 2.9 FURTHER READINGS

### Reference Books

1. *Data Structures using C and C++*, Yedidyah Langsam, Moshe J. Augenstein, Aaron M Tanenbaum, Second Edition, PHI Publications.
2. *Data Structures*, Seymour Lipschutz, Schaum's outline series, McGraw Hill

### Reference Websites

<http://www.webopedia.com>

## UNIT 3 LISTS

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### 3.0 INTRODUCTION

In the previous unit, we have discussed arrays. Arrays are data structures of fixed size. Insertion and deletion involves reshuffling of array elements. Thus, array manipulation is time-consuming and inefficient. In this unit, we will see abstract data type-lists, array implementation of lists and linked list implementation, Doubly and Circular linked lists and their applications. In linked lists, items can be added or removed easily to the end or beginning or even in the middle.

### 3.1 OBJECTIVES

After going through this unit, you will be able to:

- define and declare Lists;
- understand the terminology of Singly linked lists;
- understand the terminology of Doubly linked lists;
- understand the terminology of Circularly linked lists, and
- use the most appropriate list structure in real life situations.

### 3.2 ABSTRACT DATA TYPE-LIST

Abstract Data Type (**ADT**) is a useful tool for specifying the logical properties of data type. An ADT is a collection of values and a set of operations on those values.

Mathematically speaking, “a **TYPE** is a set, and elements of set are **Values** of that type”.

#### ADT List

A list of elements of type **T** is a finite **sequence** of elements of type **T** together with the operations of create, update, delete, testing for empty, testing for full, finding the size, traversing the elements.

In defining Abstract Data Type, we are not concerned with space or time efficiency as well as about implementation details. The elements of a list may be integers, characters, real numbers and combination of multiple data types.

Consider a real world problem, where we have a company and we want to store the details of employees. To store this, we need a data type which can store the type details containing names of employee, date of joining, etc. The list of employees may

increase depending on the recruitment and may decrease on retirements or termination of employees. To make it very simple and for understanding purposes, we are taking the name of employee field and ignoring the date of joining etc. The operations we have to perform on this list of employees are creation, insertion, deletion, visiting, etc. We define employee\_list as

```
typedef struct
{
    char name[20];
    .....
    .....
} emp_list;
```

Operations on emp\_list can be defined as

```
Create_emplist(emp_list * emp_list)
{
/* Here, we will be writing create function by taking help of 'C' programming
language. */
}
```

The list has been created and **name** is a valid entry in **emplist**, and position **p** specifies the position in the list where name has to inserted

```
insert_emplist(emp_list * emp_list, char *name, int position )
{
/* Here, we will be writing insert function by taking help of 'C' programming
language. */
}
```

```
delete_emplist(emp_list * emp_list, char *name)
```

```
{
/* Here, we will be writing delete function by taking help of 'C' programming
language. */
}
```

```
visit_emplist(emp_list * emp_list )
```

```
{
/* Here, we will be writing visit function by taking help of 'C' programming
language. */
}
```

The list can be implemented in two ways: the contiguous (Array) implementation and the linked (pointer) implementation. In contiguous implementation, the entries in the list are stored next to each other within an array. The linked list implementation uses pointers and dynamic memory allocation. We will be discussing array and linked list implementation in our next section.

### 3.3 ARRAY IMPLEMENTATION OF LISTS

In the array implementation of lists, we will use array to hold the entries and a separate counter to keep track of the number of positions are occupied. A structure will be declared which consists of Array and counter.

```
typedef struct
{
    int count;
    int entry[100];
}list;
```

For simplicity, we have taken list entry as integer. Of course, we can also take list entry as structure of employee record or student record, etc.

Count	1	2	3	4	5	6	7	8
	11	22	33	44	55	66	77	

**Insertion**

In the array implementation of lists, elements are stored in continuous locations. To add an element to the list at the end, we can add it without any problem. But, suppose if we want to insert the element at the beginning or middle of the list, then we have to rewrite all the elements after the position where the element has to be inserted. We have to shift  $(n)^{th}$  element to  $(n+1)^{th}$  position, where 'n' is number of elements in the list. The  $(n-1)^{th}$  element to  $(n)^{th}$  position and this will continue until the  $(r)$  th element to  $(r+1)^{th}$  position, where 'r' is the position of insertion. For doing this, the **count** will be incremented.

From the above example, if we want to add element '35' after element '33'. We have to shift 77 to 8<sup>th</sup> position, 66 to 7<sup>th</sup> position, so on, 44 to 5<sup>th</sup> position.

**Before Insertion**

Count	1	2	3	4	5	6	7	
	11	22	33	44	55	66	77	

**Step 1**

Count	1	2	3	4	5	6	7	8
	11	22	33	44	55	66	77	77

**Step 2**

Count	1	2	3	4	5	6	7	8
	11	22	33	44	55	66	66	77

**Step 3**

Count	1	2	3	4	5	6	7	8
	11	22	33	44	55	55	66	77

**Step 4**

Count	1	2	3	4	5	6	7	8
	11	22	33	44	44	55	66	77

**Step 5**

Count	1	2	3	4	5	6	7	8
	11	22	33	35	44	55	66	77

**Program 3.1 will demonstrate the insertion of an element at desired position**

```
/* Inserting an element into contiguous list (Linear Array) at specified position */
/* contiguous_list.C */
#include<stdio.h>
/* definition of linear list */
typedef struct
{
    int data[10];
    int count;
}list;
/*prototypes of functions */
void insert(list *, int, int);
void create(list *);
```

```
void traverse(list *);  
  
/* Definition of the insert function */  
  
void insert(list *start, int position, int element)  
{  
    int temp = start->count;  
    while( temp >= position)  
    {  
        start->data[temp+1] = start->data[temp];  
        temp --;  
    }  
  
    start->data[position] = element;  
    start->count++ ;  
}  
  
/* definition of create function to READ data values into the list */  
  
void create(list *start)  
{  
    int i=0, test=1;  
    while(test)  
    {  
        fflush(stdin);  
        printf("\n input value value for: %d:(zero to come out) ", i);  
        scanf("%d", &start->data[i]);  
  
        if(start->data[i] == 0)  
            test=0;  
        else  
            i++;  
    }  
    start->count=i;  
}
```

/\* OUTPUT FUNCTION TO PRINT ON THE CONSOLE \*/

```
void traverse(list *start)  
{  
    int i;  
    for(i = 0; i< start->count; i++)  
    {  
        printf("\n Value at the position: %d: %d ", i, start->data[i]);  
    }  
}
```

/\* main function \*/

```
void main()  
{  
    int position, element;  
    list l;  
    create(&l);  
    printf("\n Entered list as follows:\n");  
    fflush(stdin);  
    traverse(&l);  
}
```

```

fflush(stdin);
printf("\n input the position where you want to add a new data item:");
scanf("%d", &position);
fflush(stdin);
printf("\n input the value for the position:");
scanf("%d", &element);
insert(&l, position, element);
traverse(&l);
}

```

#### **Program 3.1: Insertion of an element into a linear array.**

#### **Deletion**

To delete an element in the list at the end, we can delete it without any problem. But, suppose if we want to delete the element at the beginning or middle of the list, then, we have to rewrite all the elements after the position where the element that has to be deleted exists. We have to shift  $(r+1)^{th}$  element to  $r^{th}$  position , where 'r' is position of deleted element in the list, the  $(r + 2)^{th}$  element to  $(r + 1)^{th}$  position, and this will continue until the  $(n)^{th}$  element to  $(n-1)^{th}$  position, where n is the number of elements in the list. And then the count is decremented.

From the above example, if we want to delete an element '44' from list. We have to shift 55 to 4<sup>th</sup> position, 66 to 5<sup>th</sup> position, 77 to 6<sup>th</sup> position.

#### **Before deletion**

Count	1	2	3	4	5	6	7	
	11	22	33	44	55	66	77	

#### **Step 1**

Count	1	2	3	4	5	6	7	
	11	22	33	55	55	66	77	

#### **Step 2**

Count	1	2	3	4	5	6	7	
	11	22	33	55	66	66	77	

#### **Step 3**

Count	1	2	3	4	5	6		
	11	22	33	55	66	77		

#### **Program 3.2 will demonstrate deletion of an element from the linear array**

```

/* declaration of delete_list function */
void delete_list(list *, int);

/* definition of delete_list function*/
/* the position of the element is given by the user and the element is deleted from the
list*/
void delete_list(list *start, int position)
{
    int temp = position;
    printf("\n information which we have to delete: %d", l->data[position]);

    while( temp <= start->count-1)

```

```
{  
    start->data[temp] = start->data[temp+1];  
    temp ++;  
}  
  
start->count = start->count - 1 ;  
}  
  
/* main function */  
void main()  
{  
    .....  
    .....  
  
    printf("\n input the position of element you want to delete:");  
    scanf("%d", &position);  
    fflush(stdin);  
    delete_list(&l, position);  
    traverse(&l);  
}
```

Program 3.2: Deletion of an element from the linear array

## 3.4 LINKED LISTS - IMPLEMENTATION

The Linked list is a chain of structures in which each structure consists of data as well as pointer, which stores the address (link) of the next logical structure in the list.

A linked list is a data structure used to maintain a dynamic series of data. Think of a linked list as a line of bogies of train where each bogie is connected on to the next bogie. If you know where the first bogie is, you can follow its link to the next one. By following links, you can find any bogie of the train. When you get to a bogie that isn't holding (linked) on to another bogie, you know you are at the end.

Linked lists work in the same way, except programmers usually refer to nodes instead of bogies. A single node is defined in the same way as any other user defined type or object, except that it also contains a pointer to a variable of the same type as itself.

We will be seeing how the linked list is stored in the memory of the computer. In the following *Figure 3.1*, we can see that **start** is a pointer which is pointing to the node which contains data as *madan* and the node *madan* is pointing to the node *mohan* and the last node *babu* is not pointing to any node. 1000,1050,1200 are memory addresses.

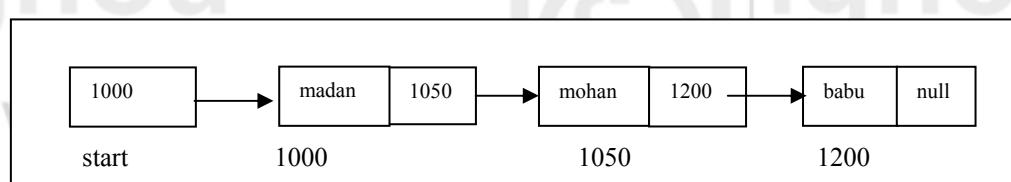


Figure 3.1: A Singly linked list

Consider the following definition:

```
typedef struct node  
{  
    int data;  
    struct node *next;  
} list;
```

Once you have a definition for a list node, you can create a list simply by declaring a pointer to the first element, called the “head”. A pointer is generally used instead of a regular variable. List can be defined as

```
list *head;
```

It is as simple as that! You now have a linked list data structure. It isn't altogether useful at the moment. You can see if the list is empty. We will be seeing how to declare and define list-using pointers in the following program 3.3.

```
#include <stdio.h>

typedef struct node
{
    int data;
    struct node *next;
} list;

int main()
{
    list *head = NULL; /* initialize list head to NULL */
    if (head == NULL)
    {
        printf("The list is empty!\n");
    }
}
```

#### **Program 3.3: Creation of a linked list**

In the next example (Program 3.4), we shall look to the process of addition of new nodes to the list with the function `create_list()`.

```
#include<stdio.h>
#include<stdlib.h>
#define NULL 0

struct linked_list
{
    int data;
    struct linked_list *next;
};

typedef struct linked_list list;

void main()
{
    list *head;
    void create(list *);
    int count(list *);
    void traverse(list *);
    head=(list *)malloc(sizeof(list));
    create(head);
    printf(" \n traversing the list \n");
    traverse(head);
    printf("\n number of elements in the list %d \n", count(head));
}

void create(list *start)
{
    printf("input the element -1111 for coming out of the loop\n");
    scanf("%d", &start->data);
```

```
if(start->data == -1111)
    start->next=NULL;
else
{
    start->next=(list*)malloc(sizeof(list));
    create(start->next);
}
}

void traverse(list *start)
{
    if(start->next!=NULL)
    {
        printf("%d --> ", start->data);
        traverse(start->next);
    }
}

int count(list *start)

{
    if(start->next == NULL)
        return 0;
    else
        return (1+count(start->next));
}
```

Program 3.4: Insertion of elements into a Linked list

### ALGORITHM (Insertion of element into a linked list)

- |        |                                                                                                                                                          |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Step 1 | Begin                                                                                                                                                    |
| Step 2 | if the list is empty or a new element comes before the start (head) element, then insert the new element as start element.                               |
| Step 3 | else, if the new element comes after the last element, then insert the new element as the end element.                                                   |
| Step 4 | else, insert the new element in the list by using the find function, find function returns the address of the found element to the insert_list function. |
| Step 5 | End.                                                                                                                                                     |

Figure 3.2 depicts the scenario of a linked list of two elements and a new element which has to be inserted between them. Figure 3.3 depicts the scenario of a linked list after insertion of a new element into the linked list of Figure 3.2.

#### Before insertion

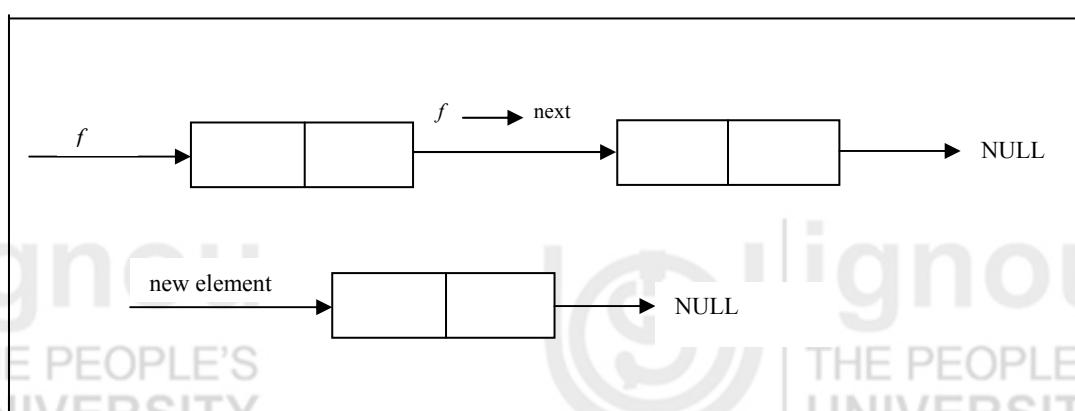


Figure 3.2: A linked list of two elements and an element that is to be inserted

#### After insertion

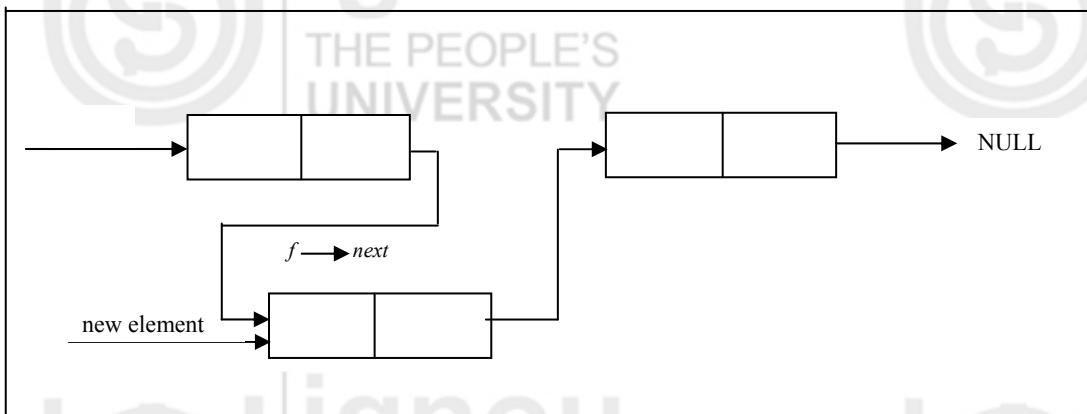


Figure 3.3: Insertion of a new element into linked list

Program 3.5 depicts the code for the insertion of an element into a linked list by searching for the position of insertion with the help of a **find** function.

#### INSERT FUNCTION

```
/*prototypes of insert and find functions */
list * insert_list(list *);
list * find(list *, int);
/*definition of insert function */
list * insert_list(list *start)
{
    list *n, *f;
    int key, element;
    printf("enter value of new element");
    scanf("%d", &element);
    printf("eneter value of key element");
    scanf("%d",&key);
    if(start->data ==key)
    {
        n=(list *)malloc(sizeof(list));
        n->data=element;
        n->next = start;
        start=n;
    }
    else
    {
        f = find(start, key);
    }
}
```

```
        if(f == NULL)
            printf("\n key is not found \n");
        else
        {
            n=(list*)malloc(sizeof(list));
            n->data=element;
            n->next=f->next;
            f->next=n;
        }
    }
    return(start);
}
/*definition of find function */
list * find(list *start, int key)
{
    if(start->next->data == key)
        return(start);
    if(start->next->next == NULL)
        return(NULL);
    else
        find(start->next, key);
}

void main()
{
    list *head;
    void create(list *);
    int count(list *);
    void traverse(list *);
    head=(list *)malloc(sizeof(list));
    create(head);
    printf(" \n traversing the created list \n");
    traverse(head);
    printf("\n number of elements in the list %d \n", count(head));
    head=insert_list(head);
    printf(" \n traversing the list after insert \n");
    traverse(head);
}
```

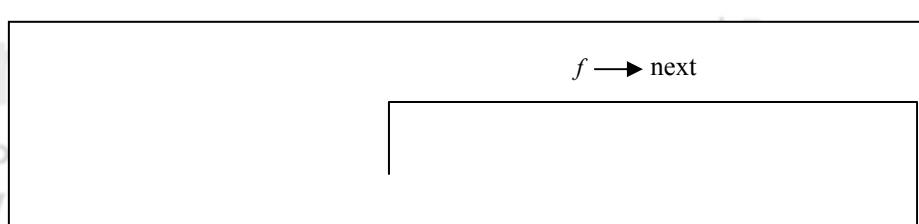
**Program 3.5: Insertion of an element into a linked list at a specific position**

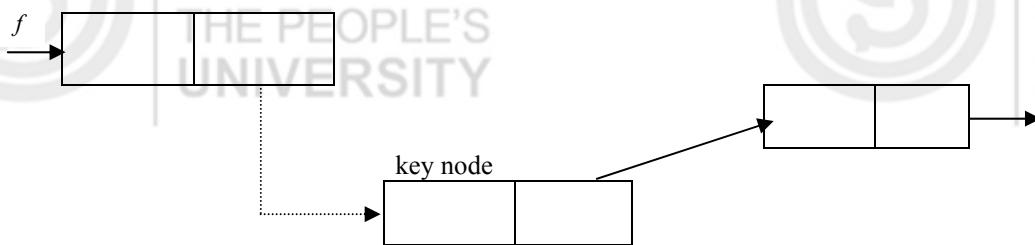
**ALGORITHM (Deletion of an element from the linked list)**

- Step 1 Begin
- Step 2 if the list is empty, then element cannot be deleted
- Step 3 else, if element to be deleted is first node, then make the start (head) to point to the second element.
- Step 4 else, delete the element from the list by calling find function and returning the found address of the element.
- Step 5 End

*Figure 3.4 depicts the process of deletion of an element from a linked list.*

**After Deletion**





**Figure 3.4: Deletion of an element from the linked list (Dotted line depicts the link prior to deletion)**

Program 3.6 depicts the deletion of an element from the linked list. It includes a function which specifically searches for the element to be deleted.

### **DELETE LIST FUNCTION**

```
/* prototype of delete_list */
list *delete_list(list *start);
list *find(list *, int);

/*definition of delete_list */
list *delete_list(list *start)
{
    int key; list * f, * temp;
    printf("\n enter the value of element to be deleted \n");
    scanf("%d", &key);
    if(start->data == key)
    {
        temp=start->next;
        free(start);
        start=temp;
    }
    else
    {
        f = find(start,key);
        if(f==NULL)
            printf("\n key not fund");
        else
        {
            temp = f->next->next;
            free(f->next);
            f->next=temp;
        }
    }
    return(start);
}
```

```
void main()
```

```

list *head;
void create(list *);
int count(list *);
void traverse(list *);
head=(list *)malloc(sizeof(list));
create(head);
```

```
    printf("\n traversing the created list \n");
    traverse(head);
    printf("\n number of elements in the list %d \n", count(head));
    head=insert(head);
    printf("\n traversing the list after insert \n");
    traverse(head);
    head=delete_list(head);
    printf("\n traversing the list after delete_list \n");
    traverse(head);
}
```

Program 3.6: Deletion of an element from the linked list by searching for element that is to be deleted

### 3.5 DOUBLY LINKED LISTS-IMPLEMENTATION

In a singly linked list, each element contains a pointer to the next element. We have seen this before. In single linked list, traversing is possible only in one direction. Sometimes, we have to traverse the list in both directions to improve performance of algorithms. To enable this, we require links in both the directions, that is, the element should have pointers to the right element as well as to its left element. This type of list is called **doubly linked list**.

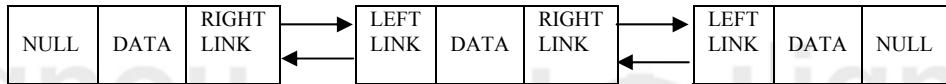


Figure 3.5: A Doubly Linked List

Doubly linked list (*Figure 3.5*) is defined as a collection of elements, each element consisting of three fields:

- pointer to left element,
- data field, and
- pointer to right element.

Left link of the leftmost element is set to NULL which means that there is no left element to that. And, right link of the rightmost element is set to NULL which means that there is no right element to that.

#### ALGORITHM (Creation)

- ```
Step 1      begin
Step 2      define a structure ELEMENT with fields
            Data
            Left pointer
            Right pointer
Step 3      declare a pointer by name head and by using (malloc()) memory
            allocation function allocate space for one element and store the
            address in head pointer
            Head = (ELEMENT *) malloc(sizeof(ELEMENT))

Step 4      read the value for head->data
            head->left = NULL
            head->right = (ELEMENT *) malloc(sizeof(ELEMENT))
Step 5      repeat step3 to create required number of elements
```

**Program 3.7 depicts the creation of a Doubly linked list.**

```
/* CREATION OF A DOUBLY LINKED LIST */
/* DBLINK.C */

#include <stdio.h>
#include <malloc.h>

struct dl_list
{
    int data;
    struct dl_list *right;
    struct dl_list *left;
};

typedef struct dl_list dlist;
void dl_create (dlist *);
void traverse (dlist *);

/* Function creates a simple doubly linked list */

void dl_create(dlist *start)
{
    printf("\n Input the values of the element -1111 to come out : ");
    scanf("%d", &start->data);
    if(start->data != -1111)
    {
        start->right = (dlist *) malloc(sizeof(dlist));
        start->right->left = start;
        start->right->right = NULL;
        dl_create(start->right);
    }
    else
        start->right = NULL;
}

/* Display the list */

void traverse (dlist *start)
{
    printf("\n traversing the list using right pointer\n");
    do {
        printf(" %d = ", start->data);
        start = start->right;
    } while (start->right); /* Show value of last start only one time */

    printf("\n traversing the list using left pointer\n");
    start=start->left;
    do
    {
        printf(" %d =", start->data);
        start = start->left;
    }while(start->right);
}
```

```
void main()
{
    dlist *head;
    head = (dlist *) malloc(sizeof(dlist));
    head->left=NULL;
    head->right=NULL;
    dl_create(head);
    printf("\n Created doubly linked list is as follows");
    traverse(head);
}
```

#### Program 3.7: Creation of a Doubly Linked List

#### OUTPUT

Input the values of the element -1111 to come out :

1

Input the values of the element -1111 to come out :

2

Input the values of the element -1111 to come out :

3

Input the values of the element -1111 to come out :

-1111

Created doubly linked list is as follows

traversing the list using right pointer

1 = 2 = 3 =

traversing the list using left pointer

3 = 2 = 1 =

---

### 3.6 CIRCULARLY LINKED LISTS IMPLEMENTATION

---

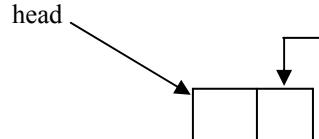
A linked list in which the last element points to the first element is called CIRCULAR linked list. The chains do not indicate first or last element; last element does not contain the NULL pointer. The external pointer provides a reference to starting element.

The possible operations on a circular linked list are:

- Insertion,
- Deletion, and
- Traversing

Figure 3.6 depicts a Circular linked list.

head



**Figure 3.6 : A Circular Linked List**

Program 3.8 depicts the creation of a Circular linked list.

```
#include<stdio.h>
#include<stdlib.h>
#define NULL 0

struct linked_list
{
    int data;
    struct linked_list *next;
};

typedef struct linked_list clist;

clist *head, *s;

void main()
{
    void create_clist(clist *);
    int count(clist *);
    void traverse(clist *);
    head=(clist *)malloc(sizeof(clist));
    s=head;
    create_clist(head);
    printf(" \n traversing the created clist and the starting address is %u \n",
    head);
    traverse(head);
    printf("\n number of elements in the clist %d \n", count(head));
}

void create_clist(clist *start)
{
    printf("input the element -1111 for coming out of the loop\n");
    scanf("%d", &start->data);
    if(start->data == -1111)
        start->next=s;
    else
    {
        start->next=(clist*)malloc(sizeof(clist));
        create_clist(start->next);
    }
}

void traverse(clist *start)
{
```

```
if(start->next!=s)
{
    printf("data is %d \t next element address is %u\n", start->data, start-
>next);
    traverse(start->next);
}
if(start->next == s)
    printf("data is %d \t next element address is %u\n", start->data, start-
>next);
}

int count(clist *start)
{
    if(start->next == s)
        return 0;
    else
        return(1+count(start->next));
```

### Program 3.8: Creation of a Circular linked list

#### ALGORITHM (Insertion of an element into a Circular Linked List)

Step 1      Begin

Step 2      if the list is empty or new element comes before the start (head) element, then insert the new element as start element.

Step 3      else, if the new element comes after the last element, then insert the new element at the end element and adjust the pointer of last element to the start element.

Step 4      else, insert the new element in the list by using the find function. find function returns the address of the found element to the insert\_list function.

Step 5      End.

If new item is to be inserted after an existing element, then, call the find function recursively to trace the ‘key’ element. The new element is inserted before the ‘key’ element by using above algorithm.

*Figure 3.7 depicts the Circular linked list with a new element that is to be inserted.*

*Figure 3.8 depicts a Circular linked list with the new element inserted between first and second nodes of Figure 3.7.*

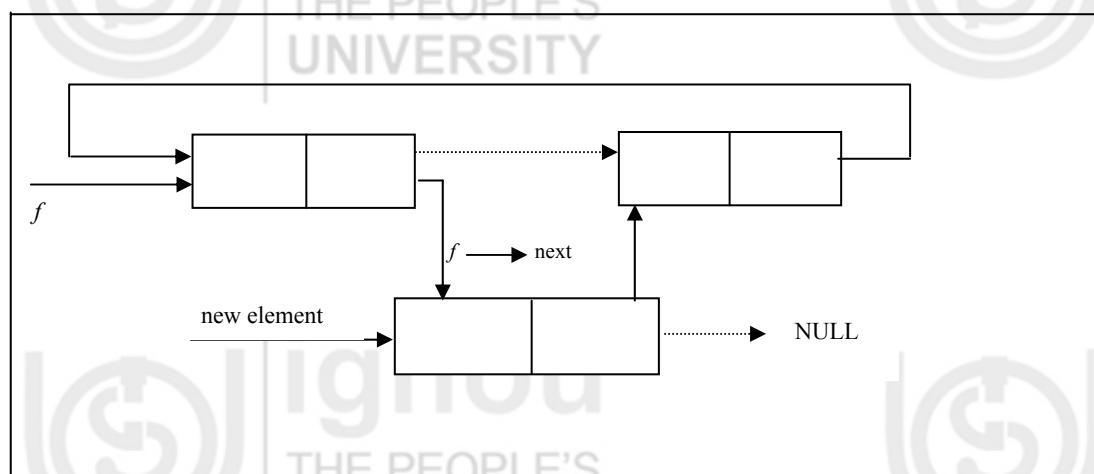


Figure 3.8: A Circular Linked List after insertion of the new element between first and second nodes  
 (Dotted lines depict the links prior to insertion)

Program 3.9 depicts the code for insertion of a node into a Circular linked list.

```
#include<stdio.h>
#include<stdlib.h>
#define NULL 0
struct linked_list
{
    int data;
    struct linked_list *next;
};
typedef struct linked_list clist;
clist *head, *s;
/* prototype of find and insert functions */
clist * find(clist *, int);
clist * insert_clist(clist *);
/*definition of insert_clist function */
clist * insert_clist(clist *start) {
    clist *n, *n1;
    int key, x;
    printf("enter value of new element");
    scanf("%d", &x);
    printf("eneter value of key element");
    scanf("%d",&key);
    if(start->data ==key)
    {
```

```
n=(clist *)malloc(sizeof(clist));
n->data=x;
n->next = start;
start=n;
}
else
{
    n1 = find(start, key);
    if(n1 == NULL)
        printf("\n key is not found\n");
    else
    {
        n=(clist*)malloc(sizeof(clist));
        n->data=x;
        n->next=n1->next;
        n1->next=n;
    }
    return(start);
}
/*definition of find function */
clist * find(clist *start, int key)
{
    if(start->next->data == key)
        return(start);
    if(start->next->next == NULL)
        return(NULL);
    else
        find(start->next, key);
}
void main()
{
    void create_clist(clist *);
    int count(clist *);
    void traverse(clist *);
    head=(clist *)malloc(sizeof(clist));
    s=head;
    create_clist(head);
    printf(" \n traversing the created clist and the starting address is %u \n",
head);
    traverse(head);
    printf("\n number of elements in the clist  %d \n", count(head));
    head=insert_clist(head);
    printf("\n traversing the clist after insert_clist and starting address is %u
\n",head);
    traverse(head);
}
void create_clist(clist *start)
{
    printf("inputthe element -1111 for coming oout of the loop\n");
    scanf("%d", &start->data);
    if(start->data == -1111)
        start->next=s;
    else
    {
        start->next=(clist*)malloc(sizeof(clist));
        create_clist(start->next);
    }
}
```

```

}
}

void traverse(clist *start)
{
    if(start->next!=s)
    {
        printf("data is %d \t next element address is %u\n", start->data, start-
>next);
        traverse(start->next);
    }
    if(start->next == s)
        printf("data is %d \t next element address is %u\n", start->data, start-
>next);
}
int count(clist *start)
{
    if(start->next == s)
        return 0;
    else
        return(1+count(start->next));
}

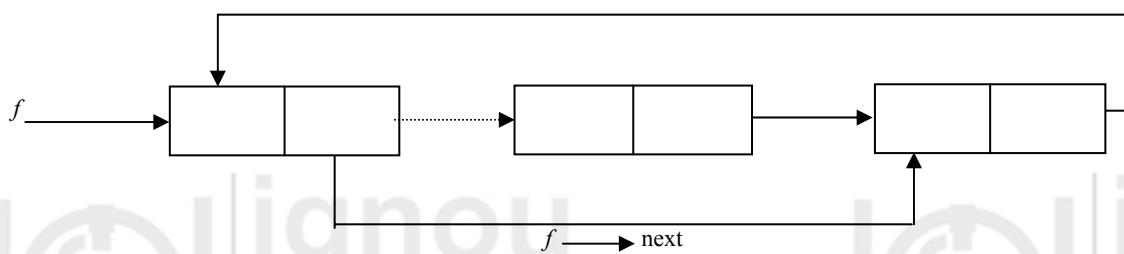
```

### **Program 3.9 Insertion of a node into a Circular Linked List**

Figure 3.9 depicts a Circular linked list from which an element was deleted.

#### **ALGORITHM (Deletion of an element from a Circular Linked List)**

- Step 1 Begin
- Step 2 if the list is empty, then element cannot be deleted.
- Step 3 else, if element to be deleted is first node, then make the start (head) to point to the second element.
- Step 4 else, delete the element from the list by calling find function and returning the found address of the element.
- Step 5 End.



**Figure 3.9 A Circular Linked List from which an element was deleted  
(Dotted line shows the linked that existed prior to deletion)**

Program 3.10 depicts the code for the deletion of an element from the Circular linked list.

```

#include<stdio.h>
#include<stdlib.h>
#define NULL 0

struct linked_list
{
    int data;
    struct linked_list *next;
};

```

```
typedef struct linked_list clist;
clist *head, *s;

/* prototype of find and delete_function*/
clist * delete_clist(clist *);
clist * find(clist *, int);

/*definition of delete_clist      */
clist *delete_clist(clist *start)
{
    int key; clist * f, * temp;
    printf("\n enter the value of element to be deleted \n");
    scanf("%d", &key);
    if(start->data == key)
    {
        temp=start->next;
        free(start);
        start=temp;
    }
    else
    {
        f = find(start,key);
        if(f==NULL)
            printf("\n key not fund");
        else
        {
            temp = f->next->next;
            free(f->next);
            f->next=temp;
        }
        return(start);
    }
    /*definition of find function */
    clist * find(clist *start, int key)
    {
        if(start->next->data == key)
            return(start);
        if(start->next->next == NULL)
            return(NULL);
        else
            find(start->next, key);
    }
}

void main()
{
    void create_clist(clist *);
    int count(clist *);
    void traverse(clist *);
    head=(clist *)malloc(sizeof(clist));
    s=head;
    create_clist(head);
    printf(" \n traversing the created clist and the starting address is %u \n",
    head);
    traverse(head);
    printf("\n number of elements in the clist  %d \n", count(head));
    head=delete_clist(head);
```

```

printf(" \n traversing the clist after delete_clistand starting address is %u
\n",head);
traverse(head);
}
void create_clist(clist *start)
{
    printf("inputthe element -1111 for coming oout of the loop\n");
    scanf("%d", &start->data);
    if(start->data == -1111)
        start->next=s;
    else
    {
        start->next=(clist*)malloc(sizeof(clist));
        create_clist(start->next);
    }
}
void traverse(clist *start)
{
    if(start->next!=s)
    {
        printf("data is %d \t next element address is %u\n", start->data, start-
>next);
        traverse(start->next);
    }
    if(start->next == s)
        printf("data is %d \t next element address is %u\n",start->data, start-
>next);
}
int count(clist *start)
{
    if(start->next == s)
        return 0;
    else
        return(1+count(start->next));
}

```

Program 3.10: Deletion of an element from the circular linked list

### 3.7 APPLICATIONS

Lists are used to maintain POLYNOMIALS in the memory. For example, we have a function  $f(x) = 7x^5 + 9x^4 - 6x^3 + 3x^2$ . Figure 3.10 depicts the representation of a Polynomial using a singly linked list. 1000,1050,1200,1300 are memory addresses.

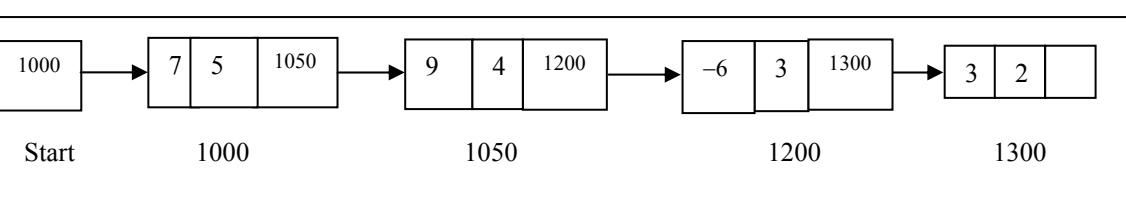


Figure 3.10: Representation of a Polynomial using a singly linked list

Polynomial contains two components, coefficient and an exponent, and 'x' is a formal parameter. The polynomial is a sum of terms, each of which consists of coefficient and an exponent. In computer, we implement the polynomial as list of structures consisting of coefficients and an exponents.

Program 3.11 accepts a Polynomial as input. It uses linked list to represent the Polynomial. It also prints the input polynomial along with the number of nodes in it.

```
/* Representation of Polynomial using Linked List */
# include <stdio.h>
# include <malloc.h>
struct link
{
    char sign;
    int coef;
    int expo;
    struct link *next;
};
typedef struct link poly;
void insertion(poly *);
void create_poly(poly *);
void display(poly *);
/* Function create a ploynomial list */
void create_poly(poly *start)
{
    char ch;
    static int i;
    printf("\n Input choice n for break: ");
    ch = getchar();
    if(ch != 'n')
    {
        printf("\n Input the sign: %d: ", i+1);
        scanf("%c", &start->sign);
        printf("\n Input the coefficient value: %d: ", i+1);
        scanf("%d", &start->coef);
        printf("\n Input the exponent value: %d: ", i+1);
        scanf("%d", &start->expo);
        fflush(stdin);
        i++;
        start->next = (poly *) malloc(sizeof(poly));
        create_poly(start->next);
    }
    else
        start->next=NULL;
}
/* Display the polynomial */
void display(poly *start)
{
    if(start->next != NULL)
    {
        printf(" %c", start->sign);
        printf(" %d", start->coef);
        printf("X^%d", start->expo);
        display(start->next);
    }
}
/* counting the number of nodes */
```

```

int count_poly(poly *start)
{
    if(start->next == NULL)
        return 0;
    else
        return(1+count_poly(start->next));
}
/* Function main */
void main()
{
    poly *head = (poly *) malloc(sizeof(poly));
    create_poly(head);
    printf("\n Total nodes = %d \n", count_poly(head));
    display(head); }
```

**Program 3.11: Representation of Polynomial using Linked list**

### Check Your Progress

- 1) Write a function to print the memory location(s) which are used to store the data in a single linked list ?
- .....  
.....  
.....

- 2) Can we use doubly linked list as a circular linked list? If yes, Explain.
- .....  
.....

- 3) Write the differences between Doubly linked list and Circular linked list.
- .....  
.....

- 4) Write a program to count the number of items stored in a single linked list.
- .....  
.....

- 5) Write a function to check the overflow condition of a list represented by an array.
- .....  
.....

---

## 3.8 SUMMARY

---

The advantage of Lists over Arrays is flexibility. Over flow is not a problem until the computer memory is exhausted. When the individual records are quite large, it may be difficult to determine the amount of contiguous storage that might be in need for the required arrays. With dynamic allocation, there is no need to attempt to allocate in advance. Changes in list, insertion and deletion can be made in the middle of the list, more quickly than in the contiguous lists.

The drawback of lists is that the links themselves take space which is in addition to the space that may be needed for data. One more drawback of lists is that they are not suited for random access. With lists, we need to traverse a long path to reach a desired node.

## 3.9 SOLUTIONS/ANSWERS

```
1) void print_location(struct node *head)
{
    temp=head;
    while(temp->next !=NULL)
    {
        printf("%u", temp);
        temp=temp->next;
    }
    printf("%u", temp);

4) void count_items(struct node *head)
{
    int count=0;
    temp=head;
    while(temp->next !=NULL)
    {
        count++;
    }
    count++;
    printf("total items = %d", count);
}

5) void Is_Overflow(int max_size, int last_element_position)
{
    if(last_element_position == max_size)
        printf("List Overflow");
    else
        printf("not Overflow");
}
```

## 3.10 FURTHER READINGS

1. *Fundamentals of Data Structures in C++* by E.Horowitz, Sahni and D.Mehta; Galgotia Publications
2. *Data Structures and Program Design in C* by Kruse, C.L.Tonodo and B.Leung; Pearson Education

### Reference Websites

- <http://www.webopedia.com>  
<http://www.ieee.org>

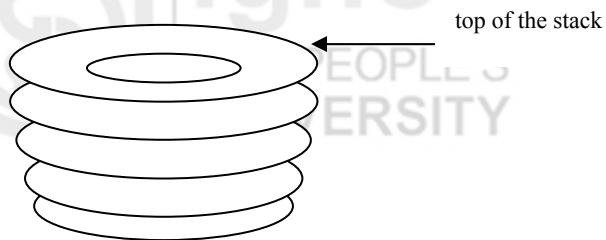
## UNIT 4 STACKS

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### 4.0 INTRODUCTION

One of the most useful concepts in computer science is stack. In this unit, we shall examine this simple data structure and see why it plays such a prominent role in the area of programming. There are certain situations when we can insert or remove an item only at the beginning or the end of the list.

A stack is a linear structure in which items may be inserted or removed only at one end called the *top of the stack*. A stack may be seen in our daily life, for example, *Figure 4.1* depicts a stack of dishes. We can observe that any dish may



**Figure 4.1: A stack of dishes**

be added or removed only from the top of the stack. It concludes that the item added last will be the item removed first. Therefore, stacks are also called LIFO (Last In First Out) or FILO (First In Last Out) lists. We also call these lists as “piles” or “push-down list”.

Generally, two operations are associated with the stacks named Push & Pop.

- *Push* is an operation used to insert an element at the top.
- *Pop* is an operation used to delete an element from the top

#### Example 4.1

Now we see the effects of push and pop operations on to an empty stack. *Figure 4.2(a)* shows (i) an empty stack; (ii) a list of the elements to be inserted on to stack;

and (iii) a variable top which helps us keep track of the location at which insertion or removal of the item would occur.

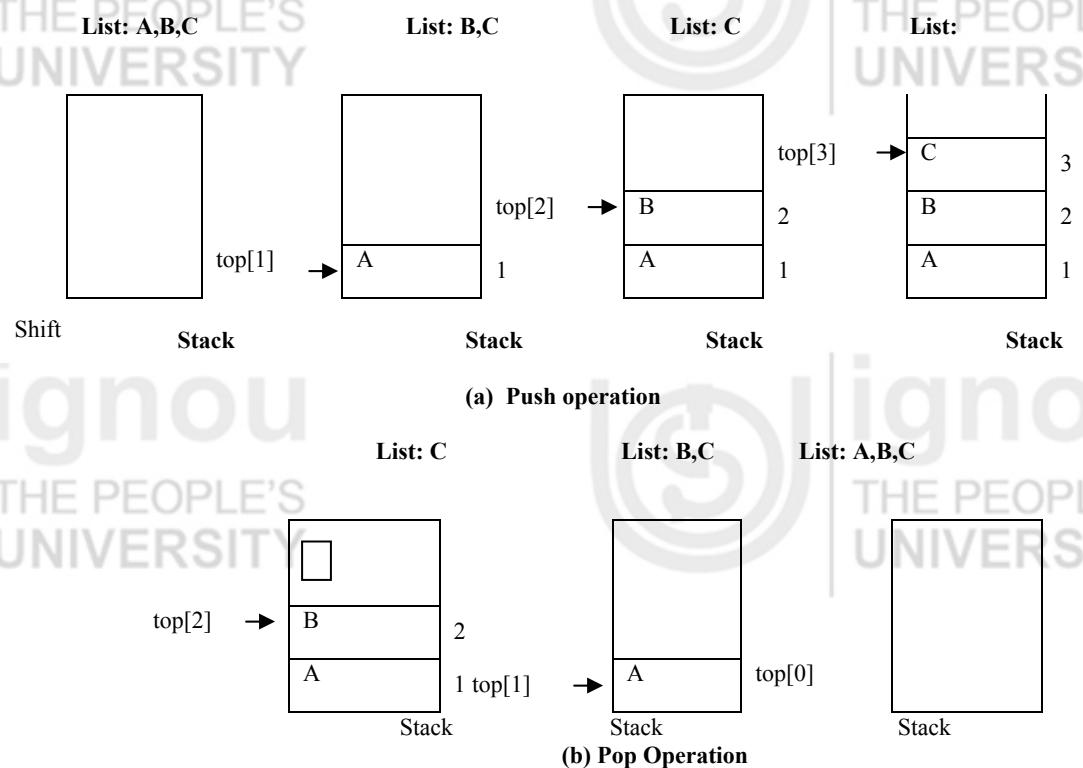


Figure 4.2: Demonstration of (a) Push operation, (b) Pop operation

Initially in *Figure 4.2(a)*, **top** contains 0, implies that the stack is empty. The list contains three elements, A, B & C. In *Figure 4.2(b)*, we remove an element A from the list of elements, push it on to stack. The value of **top** becomes 1, pointing to the location of the stack at which A is stored.

Similarly, we remove the elements B & C from the list one by one and push them on to the stack. Accordingly, the value of the **top** is incremented. *Figure 4.2(a)* explains the pushing of B and C on to stack. The **top** now contains value 3 and pointing to the location of the last inserted element C.

On the other hand, *Figure 4.2(b)* explains the working of pop operation. Since, only the top element can be removed from the stack, in *Figure 4.2(b)*, we remove the top element C (we have no other choice). C goes to the list of elements and the value of the **top** is decremented by 1. The **top** now contains value 2, pointing to B (the top element of the stack). Similarly, in *Figure 4.2(b)*, we remove the elements B and A from the stack one by one and add them to the list of elements. The value of **top** is decremented accordingly.

There is no upper limit on the number of items that may be kept in a stack. However, if a stack contains a single item and the stack is popped, the resulting stack is called empty stack. The pop operation cannot be applied to such stacks as there is no element to pop, whereas the push operation can be applied to any stack.

## 4.1 OBJECTIVES

After going through this unit, you should be able to:

- understand the concept of stack;
- implement the stack using arrays;
- implement the stack using linked lists;
- implement multiple stacks, and
- give some applications of stack.

## 4.2 ABSTRACT DATA TYPE-STACK

Conceptually, the **stack** abstract data type mimics the information kept in a pile on a desk. Informally, we first consider materials on a desk, where we may keep separate stacks for bills that need paying, magazines that we plan to read, and notes we have taken. We can perform several operations that involve a stack:

- start a new stack;
- place new information on the top of a stack;
- take the top item off of the stack;
- read the item on the top; and
- determine whether a stack is empty. (There may be nothing at the spot where the stack should be).

When discussing these operations, it is conventional to call the addition of an item to the top of the stack as a **push operation** and the deletion of an item from the top as a **pop operation**. (These terms are derived from the working of a spring-loaded rack containing a stack of cafeteria trays. Such a rack is loaded by pushing the trays down on to the springs as each diner removes a tray, the lessened weight on the springs causes the stack to pop up slightly).

## 4.3 IMPLEMENTATION OF STACK

Before programming a problem solution that uses a stack, we must decide how to represent a stack using the data structures that exist in our programming language. Stacks may be represented in the computer in various ways, usually by means of a one-way list or a linear array. Each approach has its advantages and disadvantages. A stack is generally implemented with two basic operations – push and pop. **Push** means to insert an item on to stack. The push algorithm is illustrated in *Figure 4.3(a)*. Here, **tos** is a pointer which denotes the position of top most item in the stack. Stack is represented by the array **arr** and **MAXSTACK** represents the maximum possible number of elements in the stack. The pop algorithm is illustrated in *Figure 4.3(b)*.

```

Step 1: [Check for stack overflow]
    if tos >= MAXSTACK
        print "Stack overflow" and exit
Step 2: [Increment the pointer value by one]
    tos=tos+1
Step 3: [Insert the item]
    arr[tos]=value
Step 4: Exit

```

**Figure 4.3(a): Algorithm to push an item onto the stack**

The pop operation removes the topmost item from the stack. After removal of top most value **tos** is decremented by 1.

```
Step 1: [Check whether the stack is empty]
        if tos = 0
            print "Stack underflow" and exit

Step 2: [Remove the top most item]
        value=arr[tos]
        tos=tos-1

Step 3: [Return the item of the stack]
        return(value)
```

Figure 4.3(b): Algorithm to pop an element from the stack

#### 4.3.1 Implementation of Stack Using Arrays

A Stack contains an ordered list of elements and an array is also used to store ordered list of elements. Hence, it would be very easy to manage a stack using an array. However, the problem with an array is that we are required to declare the size of the array before using it in a program. Therefore, the size of stack would be fixed. Though an array and a stack are totally different data structures, an array can be used to store the elements of a stack. We can declare the array with a maximum size large enough to manage a stack. Program 4.1 implements a stack using an array.

```
#include<stdio.h>
int choice, stack[10], top, element;

void menu();
void push();
void pop();
void showelements();

void main()
{ choice=element=1;
  top=0;
  menu();
}

void menu()
{
    printf("Enter one of the following options:\n");
    printf("PUSH 1\n POP 2\n SHOW ELEMENTS 3\n EXIT 4\n");
    scanf("%d", &choice);
    if(choice==1)
    {
        push(); menu();
    }
    if(choice==2)
    {
        pop();menu();
    }
}
```

```

        }
        if (choice==3)
        {
            showelements(); menu();
        }
    }
}

```

```

void push()
{
    if (top<=9)
    {
        printf("Enter the element to be pushed to stack:\n");
        scanf("%d", &element);
        stack[top]=element;
        ++top;
    }
    else
    {
        printf("Stack is full\n");
    }
    return;
}

```

```

void pop()
{
    if (top>0)
    {
        --top;
        element = stack[top];
        printf("Popped element:%d\n", element);
    }
    else
    {
        printf("Stack is empty\n");
    }
    return;
}

```

```

void showelements()
{
    if (top<=0)
        printf("Stack is empty\n");
    else
        for(int i=0; i<top; ++i)
            printf("%d\n", stack[i]);
}

```

#### **Program 4.1: Implementation of stack using arrays**

#### **Explanation**

The size of the stack was declared as 10. So, stack cannot hold more than 10 elements. The main operations that can be performed on a stack are push and pop. However, in a program, we need to provide two more options, namely, *showelements* and *exit*. *showelements* will display the elements of the stack. In case, the user is not interested to perform any operation on the stack and would like to get out of the program, then s/he will select *exit* option. It will log the user out of the program. *choice* is a variable which will enable the user to select the option from the push, pop, *showelements* and *exit* operations. *top* points to the index of the free location in the stack to where the next element can be pushed. *element* is the variable which accepts the integer that has to be pushed to the stack or will hold the top element of the stack that has to be popped from the stack. The array *stack* can hold at most 10 elements. *push* and *pop* will perform the operations of pushing the element to the stack and popping the element from the stack respectively.

#### 4.3.2 Implementation of Stack Using Linked Lists

In the last subsection, we have implemented a stack using an array. When a stack is implemented using arrays, it suffers from the basic limitation of an array – that is, its size cannot be increased or decreased once it is declared. As a result, one ends up reserving either too much space or too less space for an array and in turn for a stack. This problem can be overcome if we implement a stack using a linked list. In the case of a linked stack, we shall push and pop nodes from one end of a linked list.

The stack, as linked list is represented as a singly connected list. Each node in the linked list contains the data and a pointer that gives location of the next node in the list. Program 4.2 implements a stack using linked lists.

```
#include<stdio.h>
#include<conio.h>
#include<stdlib.h>

/* Definition of the structure node */
typedef struct node
{
    int data;
    struct node *next;
} ;

/* Definition of push function */
void push(node **tos,int item)
{
    node *temp;
    temp=(node*)malloc(sizeof(node)); /* create a new node dynamically */
    if(temp==NULL) /* If sufficient amount of memory is */
    {
        printf("\nError: Insufficient Memory Space"); /* return NULL to temp */
        getch();
        return;
    }
    else /* otherwise*/
    {
        temp->data=item; /* put the item in the data portion of node*/
        temp->next=*tos; /*insert this node at the front of the stack */
        *tos=temp; /* managed by linked list*/
    }
}
```

```

    }

} /*end of function push*/



/* Definition of pop function */

int pop(node **tos)
{
    node *temp;
    temp=*tos;
    int item;
    if(*tos==NULL)
        return(NULL);
    else
    {
        *tos=(*tos)->next; /* To pop an element from stack*/
        item=temp->data;   /* remove the front node of the */
        free(temp);         /* stack managed by L.L*/
        return (item);
    }
} /*end of function pop*/



/* Definition of display function */

void display(node *tos)

{
    node *temp=tos;
    if(temp==NULL) /* Check whether the stack is empty*/
    {
        printf("\nStack is empty");
        return;
    }
    else
    {
        while(temp!=NULL)
        {
            printf("\n%d",temp->data); /* display all the values of the stack*/
            temp=temp->next;          /* from the front node to the last node*/
        }
    }
} /*end of function display*/



/* Definition of main function */

void main()

{
    int item, ch;
    char choice='y';
    node *p=NULL;
    do
    {
        clrscr();
        printf("\t\t\t*****MENU*****");

```

```
printf("\n\t\tt1. To PUSH an element");
printf("\n\t\tt2. To POP an element");
printf("\n\t\tt3. To DISPLAY the elements of stack");
printf("\n\t\tt4. Exit");
scanf("%d",&ch);
switch(ch)
{
    case 1:
        printf("\nEnter an element which you want to push ");
        scanf("%d",&item);
        push(&p,item);
        break;
    case 2:
        item=pop(&p);
        if(item!=NULL);
        printf("\n Detected item is%d",item);
        break;
    case 3:
        printf("\nThe elements of stack are");
        display(p);
        break;
    case 4:
        exit(0);

    }
    /*switch closed */
    printf("\n\n\t Do you want to run it again y/n");
    scanf("%c",&choice);
}
while(choice=='y');

}
/*end of function main*/
```

#### Program 4.2: Implementation of Stack using Linked Lists

Similarly, as we did in the implementation of stack using arrays, to know the working of this program, we executed it thrice and pushed 3 elements (10, 20, 30). Then we call the function *display* in the next run to see the elements in the stack.

#### Explanation

Initially, we defined a structure called *node*. Each node contains two portions, data and a pointer that keeps the address of the next node in the list. The *Push* function will insert a node at the front of the linked list, whereas *pop* function will delete the node from the front of the linked list. There is no need to declare the size of the stack in advance as we have done in the program where in we implemented the stack using arrays since we create nodes dynamically as well as delete them dynamically. The function *display* will print the elements of the stack.

#### Check Your Progress 1

- 1) State True or False.
  - (a) Stacks are sometimes called FIFO lists.
  - (b) Stack allows Push and Pop from both ends.
  - (c) TOS (top of the stack) gives the bottom most element in the stack.

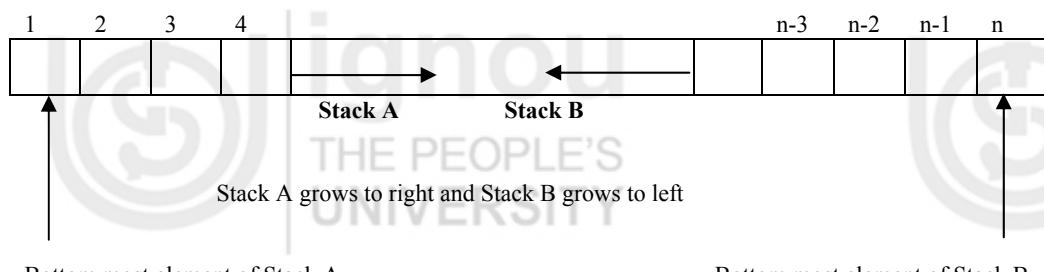
- 2) Comment on the following.
- Why is the linked list representation of the stack better than the array representation of the stack?
  - Discuss the underflow and overflow problem in stacks.

## 4.4 ALGORITHMIC IMPLEMENTATION OF MULTIPLE STACKS

So far, now we have been concerned only with the representation of a single stack. What happens when a data representation is needed for several stacks? Let us see an array  $X$  whose dimension is  $m$ . For convenience, we shall assume that the indexes of the array commence from 1 and end at  $m$ . If we have only 2 stacks to implement in the same array  $X$ , then the solution is simple.

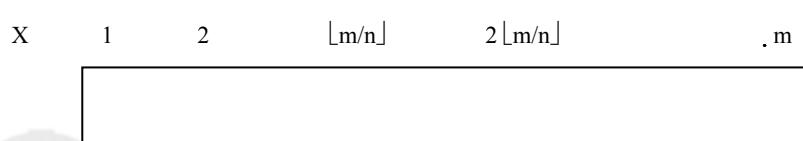
Suppose A and B are two stacks. We can define an array stack A with  $n_1$  elements and an array stack B with  $n_2$  elements. Overflow may occur when either stack A contains more than  $n_1$  elements or stack B contains more than  $n_2$  elements.

Suppose, instead of that, we define a single array stack with  $n = n_1 + n_2$  elements for stack A and B together. See the *Figure 4.4* below. Let the stack A “grow” to the right, and stack B “grow” to the left. In this case, overflow will occur only when A and B together have more than  $n = n_1 + n_2$  elements. It does not matter how many elements individually are there in each stack.



**Figure 4.4: Implementation of multiple stacks using arrays**

But, in the case of more than 2 stacks, we cannot represent these in the same way because a one-dimensional array has only two fixed points  $X(1)$  and  $X(m)$  and each stack requires a fixed point for its bottom most element. When more than two stacks, say  $n$ , are to be represented sequentially, we can initially divide the available memory  $X(1:m)$  into  $n$  segments. If the sizes of the stacks are known, then, we can allocate the segments to them in proportion to the expected sizes of the various stacks. If the sizes of the stacks are not known, then,  $X(1:m)$  may be divided into equal segments. For each stack  $i$ , we shall use  $BM(i)$  to represent a position one less than the position in  $X$  for the bottom most element of that stack.  $TM(i)$ ,  $1 \leq i \leq n$  will point to the topmost element of stack  $i$ . We shall use the boundary condition  $BM(i) = TM(i)$  iff the  $i^{\text{th}}$  stack is empty (refer to *Figure 4.5*). If we grow the  $i^{\text{th}}$  stack in lower memory indexes than the  $i+1^{\text{st}}$  stack, then, with roughly equal initial segments we have  $BM(i) = TM(i) = \lfloor m/n \rfloor (i - 1)$ ,  $1 \leq i \leq n$ , as the initial values of  $BM(i)$  and  $TM(i)$ .



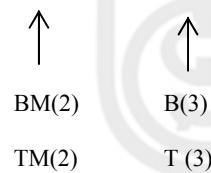


Figure 4.5: Initial configuration for  $n$  stacks in  $X(1:m)$

All stacks are empty and memory is divided into roughly equal segments.

Figure 4.6 depicts an algorithm to add an element to the  $i^{\text{th}}$  stack. Figure 4.7 depicts an algorithm to delete an element from the  $i^{\text{th}}$  stack.

```
ADD(i,e)
Step1: if TM (i)=BM (i+1)
      Print "Stack is full" and exit
Step2: [Increment the pointer value by one]
      TM (i)← TM (i)+1
      X(TM (i))← e
Step3: Exit
```

Figure 4.6: Algorithm to add an element to  $i^{\text{th}}$  stack

//delete the topmost elements of stack i.

```
DELETE(i,e)
Step1: if TM (i)=BM (i)
      Print "Stack is empty" and exit
Step2: [remove the topmost item]
      e← X(TM (i))
      TM (i)← TM(i)-1
Step3: Exit
```

Figure 4.7: Algorithm to delete an element from  $i^{\text{th}}$  stack

## 4.5 APPLICATIONS

Stacks are frequently used in evaluation of arithmetic expressions. An arithmetic expression consists of operands and operators. Polish notations are evaluated by stacks. Conversions of different notations (Prefix, Postfix, Infix) into one another are performed using stacks. Stacks are widely used inside computer when recursive functions are called. The computer evaluates an arithmetic expression written in infix notation in two steps. First, it converts the infix expression to postfix expression and then it evaluates the postfix expression. In each step, stack is used to accomplish the task.

## 4.6 SUMMARY

In this unit, we have studied how the stacks are implemented using arrays and using liked list. Also, the advantages and disadvantages of using these two schemes were discussed. For example, when a stack is implemented using arrays, it suffers from the basic limitations of an array (fixed memory). To overcome this problem, stacks are implemented using linked lists. This unit also introduced learners to the concepts of multiple stacks. The problems associated with the implementation of multiple stacks are also covered.

### Check Your Progress 2

- 1) Multiple stacks can be implemented using \_\_\_\_\_.
- 2) \_\_\_\_\_ are evaluated by stacks.
- 3) Stack is used whenever a \_\_\_\_\_ function is called.

## 4.7 SOLUTIONS / ANSWERS

### Check Your Progress 1

- 1) (a) False              (b) False  
 (c) False

### Check Your Progress 2

- 1) Arrays or Pointers
- 2) Postfix expressions
- 3) Recursive

## 4.8 FURTHER READINGS

1. *Data Structures Using C and C++*, Yedidya Langsam, Moshe J. Augenstein, Aaron M Tenenbaum, Second Edition, PHI publications.
2. *Data Structures*, Seymour Lipschutz, Schaum's Outline series, Mc GrawHill.

### Reference Websites

<http://www.cs.queensu.ca>

## UNIT 5 QUEUES

### Structure

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## 5.0 INTRODUCTION

Queue is a linear data structure used in various applications of computer science. Like people stand in a queue to get a particular service, various processes will wait in a queue for their turn to avail a service. In computer science, it is also called a FIFO (first in first out) list. In this chapter, we will study about various types of queues.

## 5.1 OBJECTIVES

After going through this unit, you should be able to

- define the queue as an abstract data type;
- understand the terminology of various types of queues such as simple queues, multiple queues, circular queues and dequeues, and
- get an idea about the implementation of different types of queues using arrays and linked lists.

## 5.2 ABSTRACT DATA TYPE-QUEUE

An important aspect of Abstract Data Types is that they describe the properties of a data structure without specifying the details of its implementation. The properties can be implemented independent of any implementation in any programming language.

*Queue* is a collection of elements, or items, for which the following operations are defined:

- createQueue(Q) : creates an empty queue Q;
- isEmpty(Q): is a boolean type predicate that returns "true" if Q exists and is empty, and returns "false" otherwise;
- addQueue(Q,item) adds the given item to the queue Q; and
- deleteQueue (Q, item) : delete an item from the queue Q;
- next(Q) removes the least recently added item that remains in the queue Q, and returns it as the value of the function;

`isEmpty (createQueue(Q))` : is always true, and  
`deleteQueue(createQueue(Q))` : error

The primitive `isEmpty(Q)` is required to know whether the queue is empty or not, because calling `next` on an empty queue should cause an error. Like stack, the situation may be such when the queue is “full” in the case of a finite queue. But we avoid defining this here as it would depend on the actual length of the Queue defined in a specific problem.

The word “queue” is like the queue of customers at a counter for any service, in which customers are dealt with in the order in which they arrive i.e. first in first out (FIFO) order. In most cases, the first customer in the queue is the first to be served.

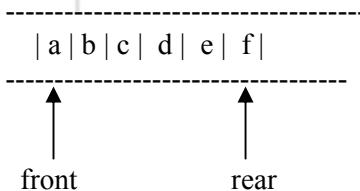
As pointed out earlier, Abstract Data Types describe the properties of a structure without specifying an implementation in any way. Thus, an algorithm which works with a “queue” data structure will work wherever it is implemented. Different implementations are usually of different efficiencies.

### 5.3 IMPLEMENTATION OF QUEUE

A physical analogy for a queue is a line at a booking counter. At a booking counter, customers go to the *rear* (end) of the line and customers are attended to various services from the *front* of the line. Unlike stack, customers are added at the rear end and deleted from the front end in a queue (FIFO).

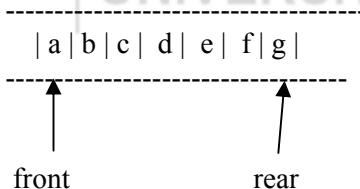
An example of the queue in computer science is print jobs scheduled for printers. These jobs are maintained in a queue. The job fired for the printer first gets printed first. Same is the scenario for job scheduling in the CPU of computer.

Like a stack, a queue also (usually) holds data elements of the same type. We usually graphically display a queue horizontally. *Figure 5.1* depicts a queue of 5 characters.



**Figure 5.1:** A queue of characters

The rule followed in a queue is that elements are added at the *rear* and come off of the *front* of the queue. After the addition of an element to the above queue, the position of rear pointer changes as shown below. Now the *rear* is pointing to the new element ‘g’ added at the rear of the queue (refer to *Figure 5.2*).



**Figure 5.2:** Queue of figure 5.1 after addition of new element

After the removal of element ‘a’ from the front, the queue changes to the following with the *front* pointer pointing to ‘b’ (refer to Figure 5.3).

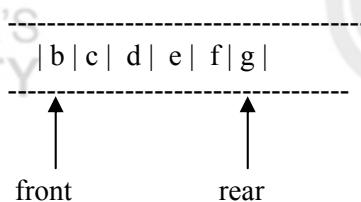


Figure 5.3: Queue of figure 5.2 after deletion of an element

#### *Algorithm for addition of an element to the queue*

- Step 1: Create a new element to be added
- Step 2: If the queue is empty, then go to step 3, else perform step 4
- Step 3: Make the front and rear point this element
- Step 4: Add the element at the end of the queue and shift the rear pointer to the newly added element.

#### *Algorithm for deletion of an element from the queue*

- Step 1: Check for Queue empty condition. If empty, then go to step 2, else go to step 3
- Step 2: Message “Queue Empty”
- Step 3: Delete the element from the front of the queue. If it is the last element in the queue, then perform *step a* else *step b*
  - a) make front and rear point to null
  - b) shift the front pointer ahead to point to the next element in the queue

### 5.3 1 Array implementation of a queue

As the stack is a list of elements, the queue is also a list of elements. The stack and the queue differ only in the position where the elements can be added or deleted. Like other liner data structures, queues can also be implemented using arrays. Program 5.1 lists the implementation of a queue using arrays.

```
#include "stdio.h"
#define QUEUE_LENGTH 50
struct queue
{
    int element[QUEUE_LENGTH];
    int front, rear, choice,x,y;
}
struct queue q;
main()
{
int choice,x;
printf ("enter 1 for add and 2 to remove element front the queue")
printf("Enter your choice")
scanf("%d",&choice);
switch (choice)

{

case 1 :
printf ("Enter element to be added :");
```

```

scanf("%d",&x);
add(&q,x);
break;

case 2 :
delete();
break;

}

add(y)
{
++q.rear;
if (q.rear < QUEUE_LENGTH)
    q.element[q.rear] = y;
else
    printf("Queue overflow")
}

delete()
{
if q.front > q.rear printf("Queue empty");
else{
    x = q.element[q.front];
    q.front++;
}
return x;
}

```

### Program 5.1: Array implementation of a Queue

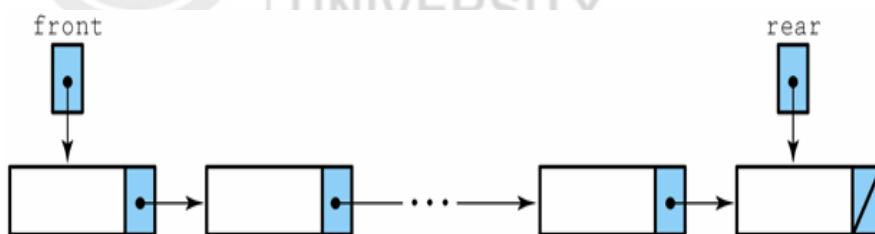
#### 5.3.2 Linked List Implementation of a queue

The basic element of a linked list is a “record” structure of at least two fields. The object that holds the data and refers to the next element in the list is called a node (refer to *Figure 5.4*).

|      |         |
|------|---------|
| Data | Ptrnext |
|------|---------|

**Figure 5.4: Structure of a node**

The *data* component may contain data of any type. *Ptrnext* is a reference to the next element in the queue structure. *Figure 5.5* depicts the linked list representation of a queue.



**Figure 5.5: A linked list representation of a Queue**

Program 5.2 gives the program segment for the addition of an element to the queue.

Program 5.3 gives the program segment for the deletion of an element from the queue.

```
add(int value)
{
    struct queue *new;
    new = (struct queue*)malloc(sizeof(queue));
    new->value = value;
    new->next = NULL;
    if (front == NULL)
    {
        queueptr = new;
        front = rear = queueptr
    }
    else
    {
        rear->next = new;
        rear=new;
    }
}
```

#### Program 5.2: Program segment for addition of an element to the queue

```
delete()
{
    int delvalue = 0;
    if (front == NULL) printf("Queue Empty");
    {
        delvalue = front->value;
        if (front->next==NULL)
        {
            free(front);
            queueptr=front=rear=NULL;
        }
        else
        {
            front=front->next;
            free(queueptr);
            queueptr=front;
        }
    }
}
```

#### Program 5.3: Program segment for deletion of an element from the queue

#### ☛ Check Your Progress 1

- 1) The queue is a data structure where addition takes place at \_\_\_\_\_ and deletion takes place at \_\_\_\_\_.
- 2) The queue is also known as \_\_\_\_\_ list.
- 3) Compare the array and linked list representations of a queue. Explain your answer.

## 5.4 IMPLEMENTATION OF MULTIPLE QUEUES

So far, we have seen the representation of a single queue, but many practical applications in computer science require several queues. Multiqueue is a data structure where multiple queues are maintained. This type of data structures are used for process scheduling. We may use one dimensional array or multidimensional array to represent a multiple queue.

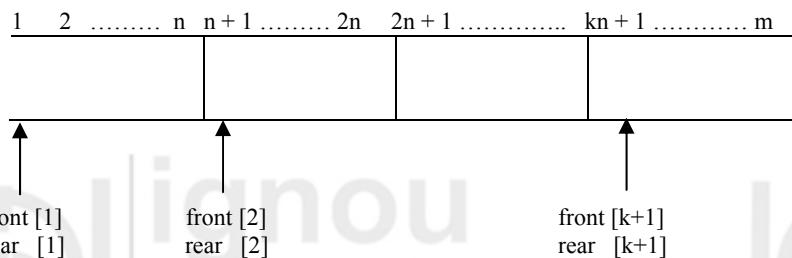


Figure 5.6: Multiple queues in an array

A multiqueue implementation using a single dimensional array with  $m$  elements is depicted in *Figure 5.6*. Each queue has  $n$  elements which are mapped to a liner array of  $m$  elements.

### Array Implementation of a multiqueue

Program 5.4 gives the program segment using arrays for the addition of an element to a queue in the multiqueue.

```
addmq(i,x) /* Add x to queue i */
{
int i,x;
++rear[i];
if ( rear[i] == front[i+1])
printf("Queue is full");
else
{
rear[i] = rear[i]+1;
mqueue[rear[i]] = x;
}
}
```

### Program 5.4: Program segment for the addition of an element to the queue

Program 5.5 gives the program segment for the deletion of an element from the queue.

```
delmq(i) /* Delete an element from queue i */
{
int i,x;
if ( front[i] == rear[i])
printf("Queue is empty");
{
x = mqueue[front[i]];
front[i] = front[i]-1 ;
return x;
}
}
```

### Program 5.5: Program segment for the deletion of an element from the queue

## 5.5 IMPLEMENTATION OF CIRCULAR QUEUES

One of the major problems with the linear queue is the lack of proper utilisation of space. Suppose that the queue can store 100 elements and the entire queue is full. So, it means that the queue is holding 100 elements. In case, some of the elements at the front are deleted, the element at the last position in the queue continues to be at the same position and there is no efficient way to find out that the queue is not full. In this way, space utilisation in the case of linear queues is not efficient. This problem is arising due to the representation of the queue.

The alternative representation is to depict the queue as circular. In case, we are representing the queue using arrays, then, a queue with  $n$  elements starts from index 0 and ends at  $n-1$ . So, clearly, the first element in the queue will be at index 0 and the last element will be at  $n-1$  when all the positions between index 0 and  $n-1$  (both inclusive) are filled. Under such circumstances, front will point to 0 and rear will point to  $n-1$ . However, when a new element is to be added and if the rear is pointing to  $n-1$ , then, it needs to be checked if the position at index 0 is free. If yes, then the element can be added to that position and rear can be adjusted accordingly. In this way, the utilisation of space is increased in the case of a circular queue.

In a circular queue, front will point to one position less to the first element anti-clock wise. So, if the first element is at position 4 in the array, then the front will point to position 3. When the circular queue is created, then both front and rear point to index 1. Also, we can conclude that the circular queue is empty in case both front and rear point to the same index. *Figure 5.7* depicts a circular queue.

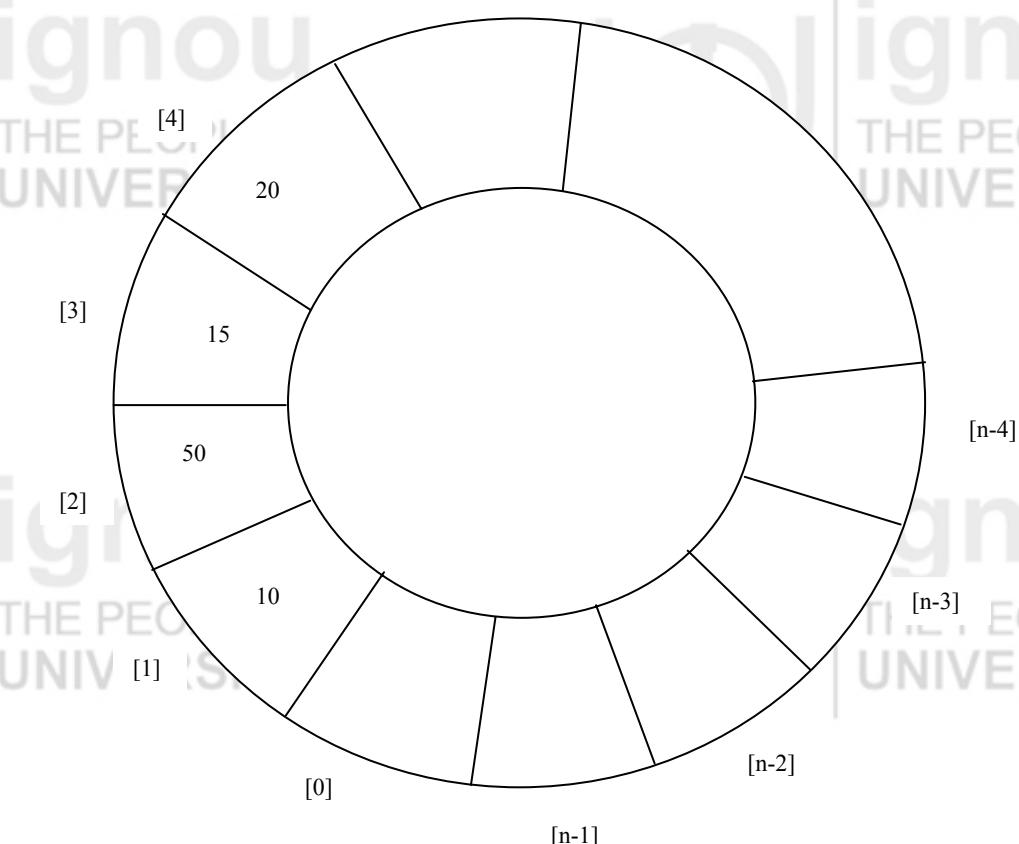


Figure 5.7 : A circular queue (Front = 0, Rear = 4)

**Algorithm for Addition of an element to the circular queue:**

**Step-1:** If “rear” of the queue is pointing to the last position then go to step-2 or else

Step-3

**Step-2:** make the “rear” value as 0

**Step-3:** increment the “rear” value by one

**Step-4:** a. if the “front” points where “rear” is pointing and the queue holds a not NULL value for it, then its a “queue overflow” state, so quit; else go to step-b

b. add the new value for the queue position pointed by the “rear”

**Algorithm for deletion of an element from the circular queue:**

**Step-1:** If the queue is empty then say “queue is empty” and quit; else continue

**Step-2:** Delete the “front” element

**Step-3:** If the “front” is pointing to the last position of the queue then go to step-4 else go to step-5

**Step-4:** Make the “front” point to the first position in the queue and quit

**Step-5:** Increment the “front” position by one

**5.5.1 Array implementation of a circular queue**

A circular queue can be implemented using arrays or linked lists. Program 5.6 gives the array implementation of a circular queue.

```
#include "stdio.h"
void add(int);
void deleteelement(void);
int max=10; /*the maximum limit for queue has been set*/
static int queue[10];
int front=0, rear=-1; /*queue is initially empty*/
void main()
{
int choice,x;
printf ("enter 1 for addition and 2 to remove element front the queue and 3 for exit");
printf("Enter your choice");
scanf("%d",&choice);
switch (choice)
{
case 1 :
printf ("Enter the element to be added :");
scanf("%d",&x);
add(x);
break;
case 2 :
deleteelement();
break;
}
}
void add(int y)
{
if(rear == max-1)
rear = 0;
else
rear = rear + 1;
if( front == rear && queue[front] != NULL)
printf("Queue Overflow");
else
```

```
        queue[rear] = y;  
    }  
  
    void deleteelement()  
    {  
        int deleted_front = 0;  
        if (front == NULL)  
            printf("Error - Queue empty");  
        else  
        {  
            deleted_front = queue[front];  
            queue[front] = NULL;  
            if (front == max-1)  
                front = 0;  
            else  
                front = front + 1;  
        }  
    }
```

#### Program 5.6: Array implementation of a Circular queue

##### 5.5.2 Linked list implementation of a circular queue

Link list representation of a circular queue is more efficient as it uses space more efficiently, of course with the extra cost of storing the pointers. Program 5.7 gives the linked list representation of a circular queue.

```
#include "stdio.h"  
struct cq  
{  
    int value;  
    int *next;  
};  
typedef struct cq *cqptr  
cqptr p, *front, *rear;  
  
main()  
{  
    int choice,x;  
  
    /* Initialise the circular queue */  
    cqptr = front = rear = NULL;  
  
    printf("Enter 1 for addition and 2 to delete element from the queue")  
    printf("Enter your choice")  
    scanf("%d",&choice);  
    switch (choice)  
    {  
  
        case 1 :  
            printf("Enter the element to be added :");  
            scanf("%d",&x);  
            add(&q,x);  
            break;  
  
        case 2 :  
            delete();  
    }  
}
```

```

        break;
    }

} **** Add element ****/
add(int value)
{
    struct cq *new;
    new = (struct cq*)malloc(sizeof(queue));
    new->value = value
    new->next = NULL;

    if (front == NULL)
    {
        cqptr = new;
        front = rear = queueptr;
    }
    else
    {
        rear->next = new;
        rear=new;
    }
}

/* ***** delete element *****/
delete()
{
    int delvalue = 0;
    if (front == NULL)
    { printf("Queue is empty");
        delvalue = front->value;
        if (front->next==NULL)
        {
            free(front);
            queueptr = front = rear = NULL;
        }
    }
    else
    {
        front=front->next;
        free(queueptr);
        queueptr = front;
    }
}

```

#### **Program 5.7 : Linked list implementation of a Circular queue**

---

## **5.6 IMPLEMENTATION OF DEQUEUE**

---

Dequeue (a double ended queue) is an abstract data type similar to queue, where addition and deletion of elements are allowed at both the ends. Like a linear queue and a circular queue, a dequeue can also be implemented using arrays or linked lists.

### 5.6.1 Array implementation of a dequeue

If a Dequeue is implemented using arrays, then it will suffer with the same problems that a linear queue had suffered. Program 5.8 gives the array implementation of a Dequeue.

```
#include "stdio.h"
#define QUEUE_LENGTH 10;
int dq[QUEUE_LENGTH];
int front, rear, choice,x,y;
main()
{
    int choice,x;
    front = rear = -1; /* initialize the front and rear to null i.e empty queue */

    printf("enter 1 for addition and 2 to remove element from the front of the queue");
    printf("enter 3 for addition and 4 to remove element from the rear of the queue");
    printf("Enter your choice");
    scanf("%d",&choice);
    switch (choice)
    {
        case 1:
            printf ("Enter element to be added :");
            scanf("%d",&x);
            add_front(x);
            break;
        case 2:
            delete_front();
            break;
        case 3:
            printf ("Enter the element to be added :");
            scanf("%d ",&x);
            add_rear(x);
            break;
        case 4:
            delete_rear();
            break;
    }
}
/************* Add at the front *****/
add_front(int y)
{
if (front == 0)
{
    printf("Element can not be added at the front");
    return;
}
else
{
    front = front - 1;
    dq[front] = y;
    if (front == -1 ) front = 0;
}
}
/************* Delete from the front *****/
delete_front()
{
if front == -1
printf("Queue empty");
```

```

else
    return dq[front];
if (front == rear)
    front = rear = -1
else
    front = front + 1;
}
***** Add at the rear *****/
add_rear(int y)
if (front == QUEUE_LENGTH - 1 )
{
printf("Element can not be added at the rear ")
return;
else
{
    rear = rear + 1;
    dq[rear] = y;
    if (rear == -1 )
        rear = 0;
}
}

***** Delete at the rear *****/
delete_rear()
{
if rear == -1
printf("deletion is not possible from rear");
else
{
    if (front == rear)
        front = rear = -1
    else
        { rear = rear - 1;
        return dq[rear];
        }
}
}

```

### **Program 5.8: Array implementation of a Dequeue**

#### **5.6.2 Linked list implementation of a deque**

Double ended queues are implemented with doubly linked lists.

A doubly link list can traverse in both the directions as it has two pointers namely left and right. The right pointer points to the next node on the right where as the left pointer points to the previous node on the left. Program 5.9 gives the linked list implementation of a Dequeue.

```

#include "stdio.h"
#define NULL 0
struct dq {
    int info;
    int *left;
    int *right;
};
typedef struct dq *dqptr;
dqptr p, tp;

```

```
dqptr head;
dqptr tail;
main()
{
    int choice, I, x;
    dqptr n;
    dqptr getnode();
    printf("\n Enter 1: Start 2 : Add at Front 3 : Add at Rear 4: Delete at Front 5:
Delete at Back");
    while (1)
    {
        printf("\n 1: Start 2 : Add at Front 3 : Add at Back 4: Delete at Front 5: Delete
at Back 6 : exit");
        scanf("%d", &choice);
        switch (choice)
        {
            case 1:
                create_list();
                break;
            case 2:
                eq_front();
                break;
            case 3:
                eq_back();
                break;
            case 4:
                dq_front();
                break;
            case 5:
                dq_back();
                break;
            case 6 :
                exit(6);
        }
    }

create_list()
{
    int I, x;
    dqptr t;
    p = getnode();
    tp = p;
    p->left = getnode();
    p->info = 10;
    p->right = getnode();
    return;
}

dqptr getnode()
{
    p = (dqptr) malloc(sizeof(struct dq));
    return p;
}

dq_empty(dq q)
{
    return q->head == NULL;
```

```

}

eq_front(dq q, void *info)
{
    if (dq_empty(q))
        q->head = q->tail = dcons(info, NULL, NULL);
    else
    {
        q-> head -> left =dcons(info, NULL, NULL);
        q->head -> left ->right = q->head;
        q ->head = q->head ->left;
    }
}

eq_back(dq q, void *info)
{
    if (dq_empty(q))
        q->head = q->tail = dcons(info, NULL, NULL)
    else
    {
        q-> tail -> right =dcons(info, NULL, NULL);
        q->tail -> right -> left = q->tail;
        q ->tail = q->tail ->right;
    }
}

dq_front(dq q)
{
    if dq is not empty
    {
        dq tp = q-> head;
        void *info = tp -> info;
        q ->head = q->head-> right;
        free(tp);
        if (q->head == NULL)
            q -> tail = NULL;
        else
            q -> head -> left = NULL;
        return info;
    }
}

dq_back(dq q)
{
    if (q!=NULL)
    {
        dq tp = q-> tail;
        *info = tp -> info;
        q ->tail = q->tail-> left;
        free(tp);
        if (q->tail == NULL)
            q -> head = NULL;
        else
            q -> tail -> right = NULL;
        return info;
    }
}

```

#### Program 5.9 : Linked list implementation of a Dequeue

### Check Your Progress 2

- 1) \_\_\_\_\_ allows elements to be added and deleted at the front as well as at the rear.
- 2) It is not possible to implement multiple queues in an Array.  
(True/False)
- 3) The index of a circular queue starts at \_\_\_\_\_.

---

## 5.7 SUMMARY

---

In this unit, we discussed the data structure *Queue*. It had two ends. One is front from where the elements can be deleted and the other if rear to where the elements can be added. A queue can be implemented using Arrays or Linked lists. Each representation is having it's own advantages and disadvantages. The problems with arrays are that they are limited in space. Hence, the queue is having a limited capacity. If queues are implemented using linked lists, then this problem is solved. Now, there is no limit on the capacity of the queue. The only overhead is the memory occupied by the pointers.

There are a number of variants of the queues. Normally, queues mean circular queues. Apart from linear queues, we also discussed circular queues in this unit. A special type of queue called Dequeue was also discussed in this unit. Dequeues permit elements to be added or deleted at either of the rear or front. We also discussed the array and linked list implementations of Dequeue.

---

## 5.8 SOLUTIONS/ANSWERS

---

### Check Your Progress 1

1. rear , front
2. First in First out (FIFO) list

### Check Your Progress 2

1. Dequeue
2. False
3. 0

---

## 5.9 FURTHER READINGS

---

### Reference Books

1. *Data Structures using C* by Aaron M.Tanenbaum, Yedidyah Langsam, Moshe J.Augenstein , PHI publications
2. *Algorithms+Data Structures = Programs* by Niklaus Wirth, PHI publications

### Reference Websites

- <http://ciips.ee.uwa.edu.au/~morris/Year2/PLDS210/queues.html>  
<http://www.cs.toronto.edu/~wayne/libwayne/libwayne.html>

# UNIT 6 TREES

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## 6.0 INTRODUCTION

Have you ever thought how does the operating system manage our files? Why do we have a hierarchical file system? How do files get saved and deleted under hierarchical directories? Well, we have answers to all these questions in this section through a hierarchical data structure called Trees! Although most general form of a tree can be defined as an **acyclic graph**, we will consider in this section only rooted tree as general tree does not have a parent-child relationship.

Tree is a data structure which allows you to associate a parent-child relationship between various pieces of data and thus allows us to arrange our records, data and files in a hierarchical fashion. Consider a Tree representing your family structure. Let us say that we start with your grand parent; then come to your parent and finally, you and your brothers and sisters. In this unit, we will go through the basic tree structures first (general trees), and then go into the specific and more popular tree called binary-trees.

## 6.1 OBJECTIVES

After going through this unit, you should be able

- to define a tree as abstract data type (ADT);
- learn the different properties of a Tree and a Binary tree;
- to implement the Tree and Binary tree, and
- give some applications of Tree.

## 6.2 ABSTRACT DATA TYPE-TREE

**Definition:** A set of data values and associated operations that are precisely specified independent of any particular implementation.

Since the data values and operations are defined with mathematical precision, rather than as an implementation in a computer language, we may reason about effects of the

operations, relationship to other abstract data types, whether a programming language implements the particular data type, etc.

Consider the following abstract data type:

### Structure Tree

type Tree = nil | fork (Element , Tree , Tree)

### Operations:

null : Tree -> Boolean  
leaf : Tree -> Boolean  
fork : (Element , Tree , Tree) -> Tree  
left : Tree -> Tree // It depicts the properties of tree that left of a tree is also a tree.  
right: Tree -> Tree  
contents: Tree -> Element  
height (nil) = 0 |  
height (fork(e,T,T')) = 1+max(height(T), height(T'))  
weight (nil) = 0 |  
weight (fork(e,T,T')) = 1+weight(T)+weight(T')

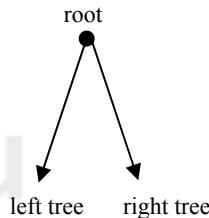


Figure 6.1: A binary tree

### Rules:

null(nil) = true // nil is an empty tree

null(fork(e, T, T'))= false // e : element , T and T' are two sub tree

leaf(fork(e, nil, nil)) = true

leaf(fork(e, T, T')) = false if not null(T) or not null(T')

leaf(nil) = error

left(fork(e, T, T')) = T

left(nil) = error

right(fork(e, T, T')) = T'

right(nil) = error

contents(fork(e, T, T')) = e

contents(nil) = error

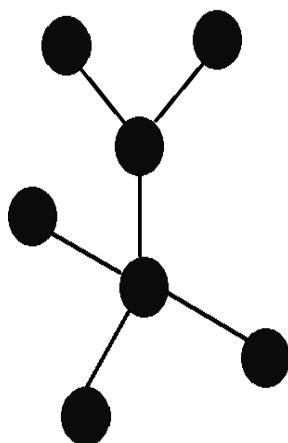
Look at the definition of Tree (ADT). A way to think of a *binary tree* is that it is either empty (nil) or contains an element and two sub trees which are themselves binary trees (Refer to *Figure 6.1*). Fork operation joins two sub tree with a parent node and

produces another Binary tree. It may be noted that a tree consisting of a single leaf is defined to be of height 1.

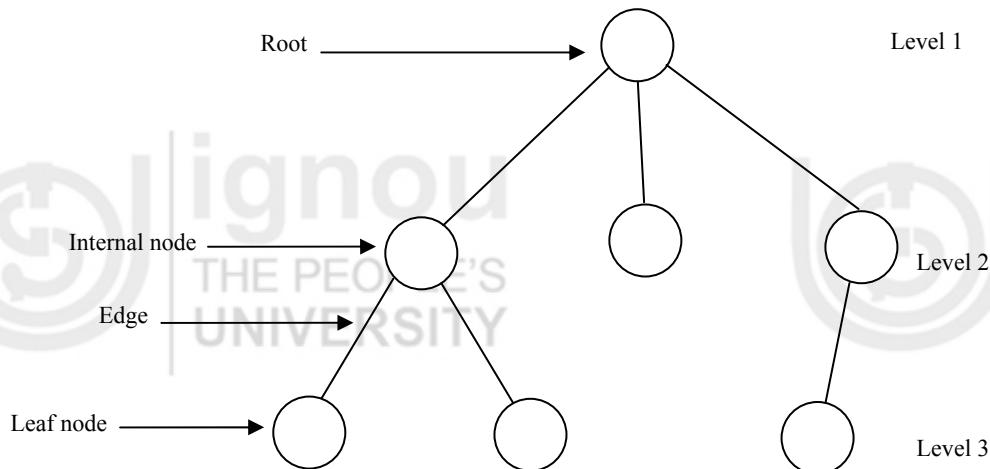
**Definition :** A tree is a connected, acyclic graph (Refer to *Figure 6.2*).

It is so connected that any node in the graph can be reached from any other node by exactly one path.

It does not contain any cycles (circuits, or closed paths), which would imply the existence of more than one path between two nodes. This is the most general kind of tree, and may be converted into the more familiar form by designating a node as the root. We can represent a tree as a construction consisting of nodes, and edges which represent a relationship between two nodes. In *Figure 6.3*, we will consider most common tree called **rooted tree**. A rooted tree has a single root node which has no parents.



**Figure 6.2 : Tree as a connected acyclic graph**



**Figure 6.3 : A rooted tree**

In a more formal way, we can define a tree  $T$  as a finite set of one or more nodes such that there is one designated node  $r$  called the root of  $T$ , and the remaining nodes in  $(T - \{ r \})$  are partitioned into  $n > 0$  disjoint subsets  $T_1, T_2, \dots, T_k$  each of which is a tree, and whose roots  $r_1, r_2, \dots, r_k$ , respectively, are children of  $r$ . The general tree is a generic tree that has one root node, and every node in the tree can have an unlimited number of child nodes. One popular use of this kind of tree is a Family Tree. A tree is an instance of a more general category called graph.

- A tree consists of nodes connected by edges.
- A root is a node without parent.
- Leaves are nodes with no children.
- The root is at level 1. The child nodes of root are at level 2. The child nodes of nodes at level 2 are at level 3 and so on.
- The depth (height) of a Binary tree is equal to the number of levels in it.
- Branching factor defines the maximum number of children to any node. So, a branching factor of 2 means a binary tree.

- Breadth defines the number of nodes at a level.
- The depth of a node M in a tree is the length of the path from the root of the tree to M.
- A node in a Binary tree has at most 2 children.

The following are the properties of a Tree.

*Full Tree* : A tree with all the leaves at the same level, and all the non-leaves having the same degree

- Level  $h$  of a full tree has  $d^{h-1}$  nodes.
- The first  $h$  levels of a full tree have  $1 + d + d^2 + d^3 + d^4 + \dots + d^{h-1} = (d^h - 1)/(d - 1)$  nodes where  $d$  is the degree of nodes.
- The number of edges = the number of nodes - 1 (Why? Because, an edge represents the relationship between a child and a parent, and every node has a parent except the root).
- A tree of height  $h$  and degree  $d$  has at most  $d^h - 1$  elements.

#### Complete Trees

*A complete tree is a k-ary position tree in which all levels are filled from left to right. There are a number of specialized trees.*

They are binary trees, binary search trees, AVL-trees, red-black trees, 2-3 trees.

#### Data structure- Tree

Tree is a dynamic data structures. Trees can expand and contract as the program executes and are implemented through pointers. A tree deallocates memory when an element is deleted.

Non-linear data structures: Linear data structures have properties of ordering relationship (can the elements/nodes of tree be sorted?). There is no first node or last node. There is no ordering relationship among elements of tree.

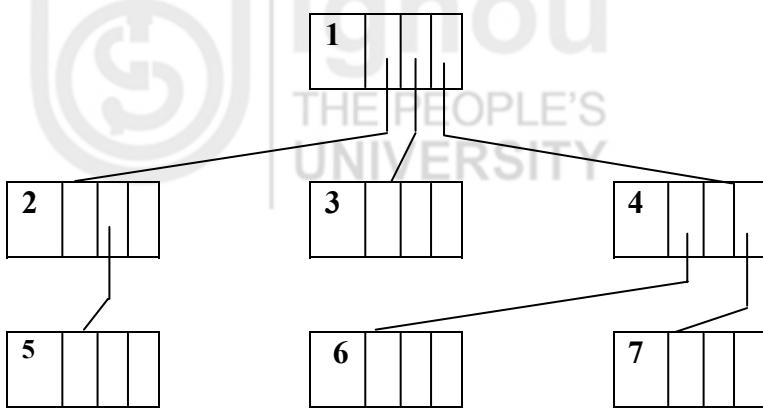
Items of a tree can be partially ordered into a hierarchy via parent-child relationship. Root node is at the top of the hierarchy and leafs are at the bottom layer of the hierarchy. Hence, trees can be termed as hierarchical data structures.

## 6.3 IMPLEMENTATION OF TREE

The most common way to add nodes to a general tree is to first find the desired parent of the node you want to insert, then add the node to the parent's child list. The most common implementations insert the nodes one at a time, but since each node can be considered a tree on its own, other implementations build up an entire sub-tree before adding it to a larger tree. As the nodes are added and deleted dynamically from a tree, tree are often implemented by link lists. However, it is simpler to write algorithms for a data representation where the numbers of nodes are fixed. *Figure 6.4* depicts the structure of the node of a general k-ary tree.

|      |       |       |       |        |
|------|-------|-------|-------|--------|
| Data | link1 | link2 | ..... | link k |
|------|-------|-------|-------|--------|

Figure 6.4 : Node structure of a general k-ary tree



**Figure 6.5:** A linked list representation of tree (3-ary tree)

Figure 6.5 depicts a tree with one data element and three pointers. The number of pointers required to implement a general tree depend of the maximum degree of nodes in the tree.

## 6.4 TREE TRAVERSALS

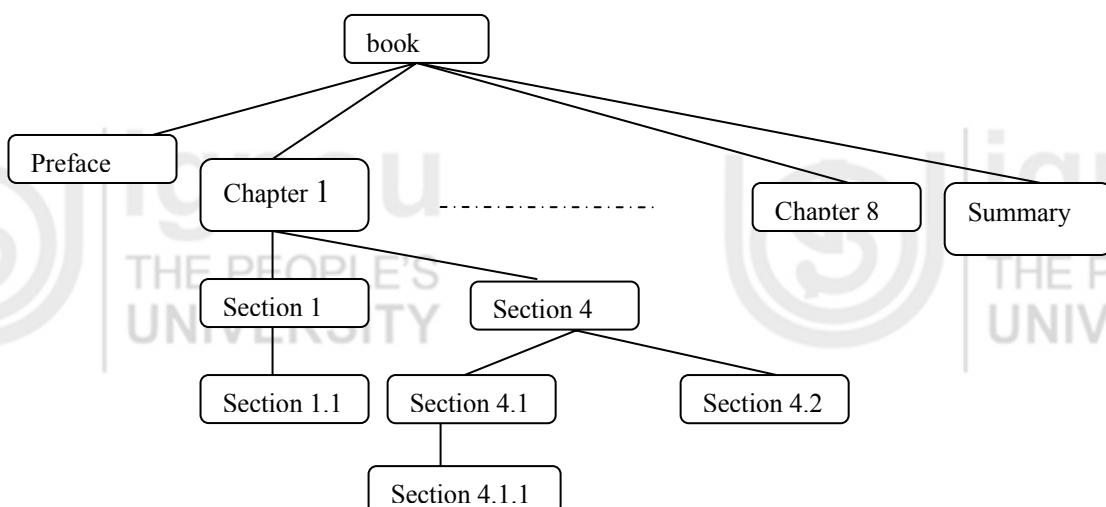
There are three types of tree traversals, namely, Preorder, Postorder and Inorder.

*Preorder traversal:* Each node is visited before its children are visited; the root is visited first.

**Algorithm for pre order traversal:**

1. visit root node
2. traverse left sub-tree in preorder
3. traverse right sub-tree in preorder

*Example of pre order traversal:* Reading of a book, as we do not read next chapter unless we complete all sections of previous chapter and all it's sections (refer to Figure 6.6).



**Figure 6.6 :** Reading a book : A preorder tree traversal

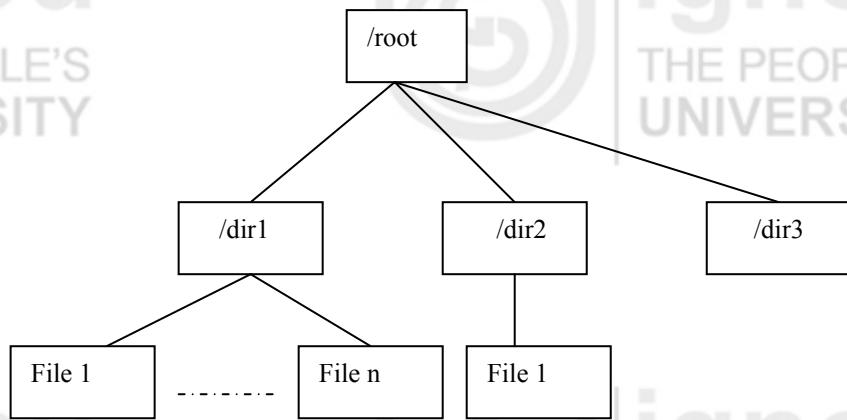
As each node is traversed only once, the time complexity of preorder traversal is  $T(n) = O(n)$ , where n is number of nodes in the tree.

*Postorder traversal:* The children of a node are visited before the node itself; the root is visited last. Every node is visited after its descendants are visited.

**Algorithm for postorder traversal:**

1. traverse left sub-tree in post order
2. traverse right sub-tree in post order
3. visit root node.

Finding the space occupied by files and directories in a file system requires a postorder traversal as the space occupied by directory requires calculation of space required by all files in the directory (children in tree structure) (refer to *Figure 6.7*)



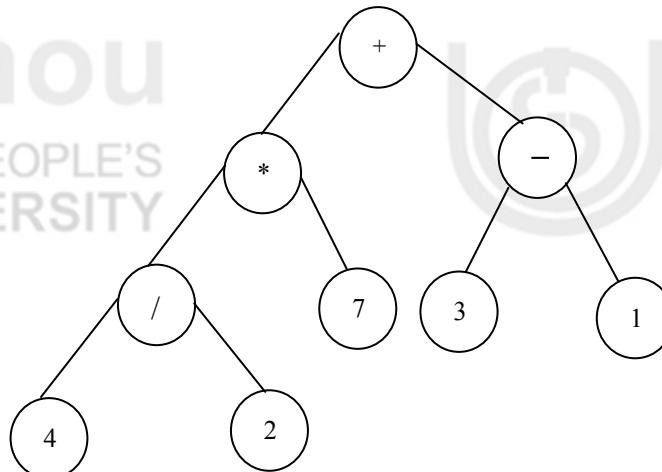
**Figure 6.7 : Calculation of space occupied by a file system : A post order traversal**

As each node is traversed only once, the time complexity of post order traversal is  $T(n) = O(n)$ , where n is number of nodes in the tree.

*Inorder traversal:* The left sub tree is visited, then the node and then right sub-tree.

**Algorithm for inorder traversal:**

1. traverse left sub-tree
2. visit node
3. traverse right sub-tree



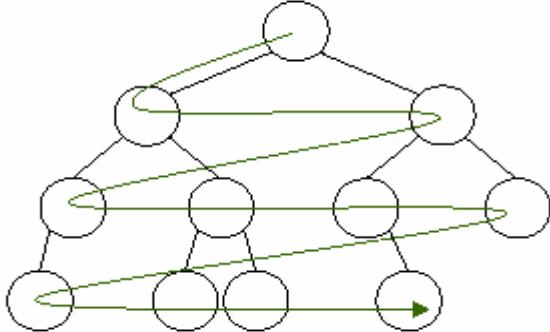
**Figure 6.8 : An expression tree : An inorder traversal**

Inorder traversal can be best described by an expression tree, where the operators are at parent node and operands are at leaf nodes.

Let us consider the above expression tree (refer to *Figure 6.8*). The preorder, postorder and inorder traversal are given below:

preorder Traversal : + \* / 4 2 7 - 3 1  
 postorder traversal : 4 2 / 7 \* 3 1 - +  
 inorder traversal : - (((4 / 2) \* 7) + (3 - 1))

There is another tree traversal (of course, not very common) is called level order, where all the nodes of the same level are travelled first starting from the root (refer to *Figure 6.9*).



**Figure 6.9: Tree Traversal: Level Order**

### Check Your Progress 1

- 1) If a tree has 45 edges, how many vertices does it have?
- 2) Suppose a full 4-ary tree has 100 leaves. How many internal vertices does it have?
- 3) Suppose a full 3-ary tree has 100 internal vertices. How many leaves does it have?
- 4) Prove that if T is a full m-ary tree with v vertices, then T has  $((m-1)v+1)/m$  leaves.

---

## 6.5 BINARY TREES

---

A binary tree is a special tree where each non-leaf node can have atmost two child nodes. Most important types of trees which are used to model yes/no, on/off, higher/lower, i.e., binary decisions are binary trees.

Recursive Definition: A binary tree is either empty or a node that has left and right sub-trees that are binary trees. Empty trees are represented as boxes (but we will almost always omit the boxes).

In a formal way, we can define a binary tree as a finite set of nodes which is either empty or partitioned in to sets of  $T_0, T_l, T_r$ , where  $T_0$  is the root and  $T_l$  and  $T_r$  are left and right binary trees, respectively.

- If a binary tree contains  $n$  nodes, then it contains exactly  $n - 1$  edges;
- A Binary tree of height  $h$  has  $2^h - 1$  nodes or less.
- If we have a binary tree containing  $n$  nodes, then the height of the tree is at most  $n$  and at least ceiling  $\log_2(n + 1)$ .
- If a binary tree has  $n$  nodes at a level  $l$  then, it has at most  $2n$  nodes at a level  $l+1$
- The total number of nodes in a binary tree with depth  $d$  (root has depth zero) is  $N = 2^0 + 2^1 + 2^2 + \dots + 2^d = 2^{d+1} - 1$

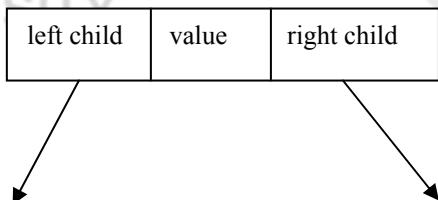
*Full Binary Trees:* A binary tree of height  $h$  which had  $2^h - 1$  elements is called a Full Binary Tree.

*Complete Binary Trees:* A binary tree whereby if the height is  $d$ , and all levels, except possibly level  $d$ , are completely full. If the bottom level is incomplete, then it has all nodes to the left side. That is the tree has been filled in the level order from left to right.

## 6.6 IMPLEMENTATION OF A BINARY TREE

Like general tree, binary trees are implemented through linked lists. A typical node in a Binary tree has a structure as follows (refer to *Figure 6.10*):

```
struct NODE
{
    struct NODE *leftchild;
    int nodevalue;           /* this can be of any data type */
    struct NODE *rightchild;
};
```



The ‘left child’ and ‘right child’ are pointers to another tree-node. The “leaf node” (not shown) here will have NULL values for these pointers.

**Figure 6.10 : Node structure of a binary tree**

The binary tree creation follows a very simple principle. For the new element to be added, compare it with the current element in the tree. If its value is less than the current element in the tree, then move towards the left side of that element or else to its right. If there is no sub tree on the left, then make your new element as the left child of that current element or else compare it with the existing left child and follow the same rule. Exactly, the same has to be done for the case when your new element is greater than the current element in the tree but this time with the right child. Though this logic is followed for the creation of a Binary tree, this logic is often suitable to search for a key value in the binary tree.

### Algorithm for the implementation of a Binary tree:

Step-1: If value of new element < current element, then go to step-2 or else step -3

Step-2: If the current element does not have a left sub-tree, then make your new

element the left child of the current element; else make the existing left child as your current element and go to step-1

Step-3: If the current element does not have a right sub-tree, then make your new element the right child of the current element; else make the existing right child as your current element and go to step-1

Program 6.1 depicts the segment of code for the creation of a binary tree.

```
struct NODE
{
    struct NODE *left;
    int value;
    struct NODE *right;
};

create_tree( struct NODE *curr, struct NODE *new )
{
    if(new->value <= curr->value)
    {
        if(curr->left != NULL)
            create_tree(curr->left, new);
        else
            curr->left = new;
    }
    else
    {
        if(curr->right != NULL)
            create_tree(curr->right, new);
        else
            curr->right = new;
    }
}
```

#### Program 6.1 : Binary tree creation

#### *Array-based representation of a Binary Tree*

Consider a complete binary tree T having n nodes where each node contains an item (value). Label the nodes of the complete binary tree T from top to bottom and from left to right 0, 1, ..., n-1. Associate with T the array A where the  $i^{\text{th}}$  entry of A is the item in the node labelled i of T,  $i = 0, 1, \dots, n-1$ . Figure 6.11 depicts the array representation of a Binary tree of Figure 6.16.

Given the index  $i$  of a node, we can easily and efficiently compute the index of its parent and left and right children:

Index of Parent:  $(i - 1)/2$ , Index of Left Child:  $2i + 1$ , Index of Right Child:  $2i + 2$ .

| Node # | Item | Left child | Right child |
|--------|------|------------|-------------|
| 0      | A    | 1          | 2           |
| 1      | B    | 3          | 4           |
| 2      | C    | -1         | -1          |
| 3      | D    | 5          | 6           |
| 4      | E    | 7          | 8           |
| 5      | G    | -1         | -1          |
| 6      | H    | -1         | -1          |
| 7      | I    | -1         | -1          |
| 8      | J    | -1         | -1          |
| 9      | ?    | ?          | ?           |

Figure 6.11 : Array Representation of a Binary Tree

First column represents index of node, second column consist of the item stored in the node and third and fourth columns indicate the positions of left and right children (-1 indicates that there is no child to that particular node.)

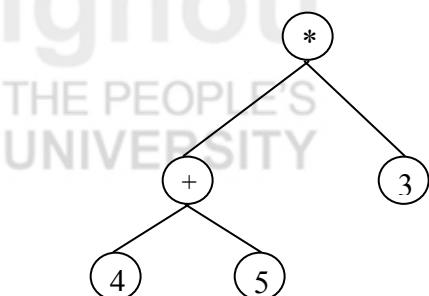
## 6.7 BINARY TREE TRAVERSALS

We have already discussed about three tree traversal methods in the previous section on general tree. The same three different ways to do the traversal – preorder, inorder and postorder are applicable to binary tree also.

Let us discuss the inorder binary tree traversal for following binary tree (refer to *Figure 6.12*):

We start from the root i.e. \* We are supposed to visit its left sub-tree then visit the node itself and its right sub-tree. Here, root has a left sub-tree rooted at +. So, we move to + and check for its left sub-tree (we are suppose repaeat this for every node). Again, + has a left sub-tree rooted at 4. So, we have to check for 4's left sub-tree now, but 4 doesn't have any left sub-tree and thus we will visit node 4 first (print in our case) and check for its right sub-tree. As 4 doesn't have any right sub-tree, we'll go back and visit node +; and check for the right sub-tree of +. It has a right sub-tree rooted at 5 and so we move to 5. Well, 5 doesn't have any left or right sub-tree. So, we just visit 5 (print 5)and track back to +. As we have already visited + so we track back to \*. As we are yet to visit the node itself and so we visit \* before checking for the right sub-tree of \*, which is 3. As 3 does not have any left or right sub-trees, we visit 3.

So, the inorder traversal results in 4 + 5 \* 3



### Algorithm: Inorder

- Step-1: For the current node, check whether it has a left child. If it has, then go to step-2 or else go to step-3
- Step-2: Repeat step-1 for this left child
- Step-3: Visit (i.e. printing the node in our case) the current node
- Step-4: For the current node check whether it has a right child. If it has, then go to step-5
- Step-5: Repeat step-1 for this right child

Figure 6.12 : A binary tree

The preoreder and postorder traversals are similar to that of a general binary tree. The general thing we have seen in all these tree traversals is that the traversal mechanism is inherently recursive in nature.

### 6.7.1 Recursive Implementation of Binary Tree Traversals

There are three classic ways of recursively traversing a binary tree. In each of these, the left and right sub-trees are visited recursively and the distinguishing feature is **when the element in the root is visited or processed**.

Program 6.2, Program 6.3 and Program 6.4 depict the inorder, preorder and postorder traversals of a Binary tree.

```
struct NODE  
{
```

```

struct NODE *left;
int value; /* can be of any type */
struct NODE *right;
};

inorder(struct NODE *curr)
{
if(curr->left != NULL) inorder(curr->left);
printf("%d", curr->value);

if(curr->right != NULL) inorder(curr->right);

}

```

#### **Program 6.2 : Inorder traversal of a binary tree**

```

struct NODE
{
struct NODE *left;
int value; /* can be of any type */
struct NODE *right;
};

preorder(struct NODE *curr)
{
printf("%d", curr->value);
if(curr->left != NULL) preorder(curr->left);
if(curr->right != NULL) preorder(curr->right);

}

```

#### **Program 6.3 : Preorder traversal of a binary tree**

```

struct NODE
{
struct NODE *left;
int value; /* can be of any type */
struct NODE *right;
};

postorder(struct NODE *curr)
{
if(curr->left != NULL) postorder(curr->left);
if(curr->right != NULL) postorder(curr->right);

printf("%d", curr->value);

}

```

#### **Program 6.4 : Postorder traversal of a binary tree**

In a preorder traversal, the root is visited first (pre) and then the left and right sub-trees are traversed. In a postorder traversal, the left sub-tree is visited first, followed by right sub-tree which is then followed by root. In an inorder traversal, the left sub-tree is visited first, followed by root, followed by right sub-tree.

## 6.7.2 Non-recursive implementation of binary tree traversals

As we have seen, as the traversal mechanisms were inherently recursive, the implementation was also simple through a recursive procedure. However, in the case of a non-recursive method for traversal, it has to be an iterative procedure; meaning, all the steps for the traversal of a node have to be under a loop so that the same can be applied to all the nodes in the tree.

### Algorithm : Non-recursive preorder binary tree traversal

```
Stack S
push root onto S
repeat until S is empty
{
    v = pop S
    if v is not NULL
        visit v
        push v's right child onto S
        push v's left child onto S
}
```

Program 6.5 depicts the program segment for the implementation of non-recursive preorder traversal.

```
/* preorder traversal of a binary tree, implemented using a stack */
void preorder(binary_tree_type *tree)
{
    stack_type *stack;
    stack = create_stack();
    push(tree, stack); /* push the first element of the tree to the stack */
    while (!empty(stack))
    {
        tree = pop(stack);
        visit(tree);
        push(tree->right, stack); /* push right child to the stack */
        push(tree->left, stack); /* push left child to the stack */
    }
}
```

### Program 6.5: Non-recursive implementation of preorder traversal

In the worst case, for preorder traversal, the stack will grow to size  $n/2$ , where  $n$  is number of nodes in the tree. Another method of traversing binary tree non-recursively which does not use stack requires pointers to the parent node (called threaded binary tree).

A threaded binary tree is a binary tree in which every node that does not have a right child has a THREAD (a third link) to its INORDER successor. By doing this threading we avoid the recursive method of traversing a tree and use of stack, which makes use of a lot of memory and time.

A node structure of threaded binary is :

The node structure for a threaded binary tree varies a bit and its like this –

```
struct NODE
```

```
{
```

```

struct NODE *leftchild;
int node_value;
struct NODE *rightchild;
struct NODE *thread; /* third pointer to it's inorder successor */
}

```

## 6.8 APPLICATIONS

Trees are used enormously in computer programming. These can be used for improving database search times (binary search trees, 2-3 trees, AVL trees, red-black trees), Game programming (minimax trees, decision trees, pathfinding trees), 3D graphics programming (quadtrees, octrees), Arithmetic Scripting languages (arithmetic precedence trees), Data compression (Huffman trees), and file systems (B-trees, sparse indexed trees, tries). Figure 6.13 depicts a tic-tac-toe game tree showing various stages of game.

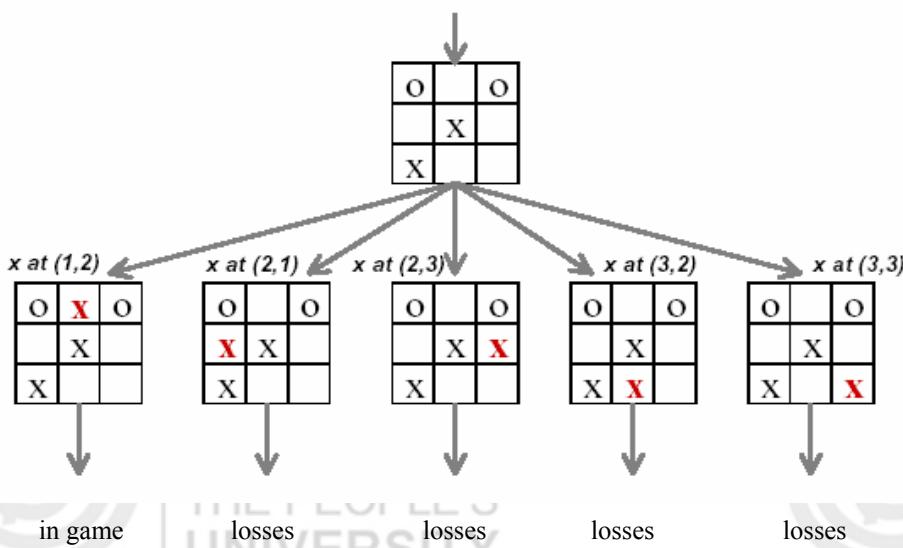


Figure 6.13 : A tic-tac-toe game tree showing various stages of game

In all of the above scenario except the first one, the player (playing with X) ultimately loses in subsequent moves.

The General tree (also known as Linked Trees) is a generic tree that has one root node, and every node in the tree can have an unlimited number of child nodes. One popular use of this kind of tree is in Family Tree programs. In game programming, many games use these types of trees for decision-making processes as shown above for tic-tac-toe. A computer program might need to make a decision based on an event that happened.

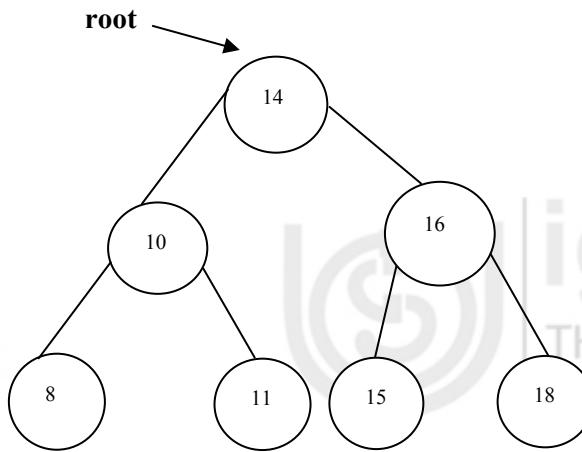
But this is just a simple tree for demonstration. A more complex AI decision tree would definitely have a lot more options. The interesting thing about using a tree for decision-making is that the options are cut down for every level of the tree as we go down, greatly simplifying the subsequent moves and improving the speed at which the AI program makes a decision.

The big problem with tree based level progressions, however, is that sometimes the tree can get too large and complex as the number of moves (level in a tree) increases. Imagine a game offering just two choices for every move to the next level at the end of each level in a ten level game. This would require a tree of 1023 nodes to be created.

Binary trees are used for searching keys. Such trees are called Binary Search trees(refer to *Figure 6.14*).

A Binary Search Tree (BST) is a binary tree with the following properties:

1. The key of a node is always greater than the keys of the nodes in its left sub-tree
2. The key of a node is always smaller than the keys of the nodes in its right sub-tree



**Figure 6.14 : A binary search tree (BST)**

It may be seen that when nodes of a BST are traversed by inorder traversal, the keys appear in sorted order:

```

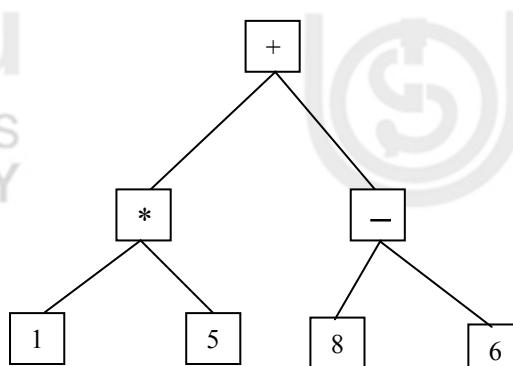
inorder(root)
{
    inorder(root.left)
    print(root.key)
    inorder(root.right)
}
  
```

Binary Trees are also used for evaluating expressions.

A binary tree can be used to represent and evaluate arithmetic expressions.

1. If a node is a leaf, then the element in it specifies the value.
2. If it is not a leaf, then evaluate the children and combine them according to the operation specified by the element.

*Figure 6.15* depicts a tree which is used to evaluate expressions.



**Figure 6.15 : Expression tree for  $1 * 5 + 8 - 6$**

## Check Your Progress 2

Trees

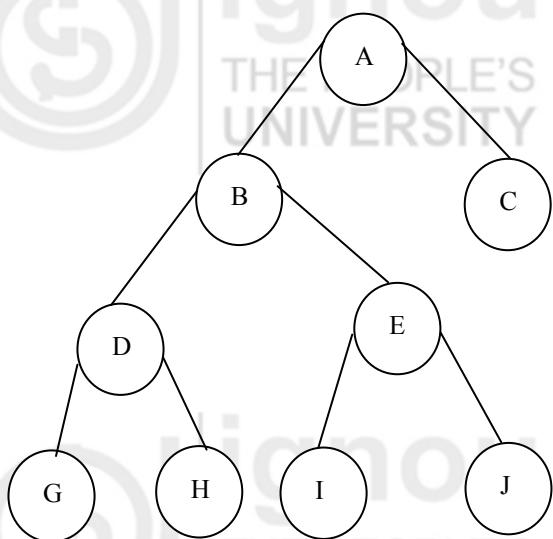


Figure 6.16 : A binary tree

- 1) With reference to *Figure 6.16*, find
  - a) the leave nodes in the binary tree
  - b) sibling of J
  - c) Parent node of G
  - d) depth of the binary tree
  - e) level of node J
- 2) Give preorder, post order, inorder and level order traversal of above binary tree
- 3) Give array representation of the binary tree of *Figure 6.12*
- 4) Show that in a binary tree of N nodes, there are N+1 children with both the links as null (leaf node).

---

## 6.9 SUMMARY

---

Tree is one of the most widely used data structure employed for representing various problems. We studied tree as a special case of an acyclic graph. However, rooted trees are most prominent of all trees. We discussed definition and properties of general trees with their applications. Various tree traversal methods are also discussed.

Binary tree are the special case of trees which have at most two children. Binary trees are mostly implemented using link lists. Various tree traversal mechanisms include inorder, preorder and post order. These tree traversals can be implemented using recursive procedures and non-recursive procedures. Binary trees have wider applications in two way decision making problems which use yes/no, true/false etc.

---

## 6.10 SOLUTIONS / ANSWERS

---

### Check Your Progress 1

- 1) If a tree has e edges and n vertices, then  $e=n - 1$ . Hence, if a tree has 45 edges, then it has 46 vertices.
- 2) A full 4-ary tree with 100 leaves has  $i=(100 - 1)/(4 - 1)=33$  internal vertices.
- 3) A full 3-ary tree with 100 internal vertices has  $l = (3 - 1)*100+ 1=201$  leaves

## Check Your Progress 2

- 1) Answers
  - a. G,H,I and J
  - b. I
  - c. D
  - d. 4
  - e. 4
- 2) Preorder : ABCDHEIJC Postorder : GHDIJEBCA Inorder : GDHBIEFAC level-order: ABCDEGHIJ
- 3) Array representation of the tree in *Figure 6.12*

| Index of Node | Item | Left child | Right child |
|---------------|------|------------|-------------|
| 0             | *    | 1          | 2           |
| 1             | +    | 3          | 4           |
| 2             | 3    | -1         | -1          |
| 3             | 4    | -1         | -1          |
| 4             | 5    | -1         | -1          |
| 5             | ?    | ?          | ?           |

---

## 6.11 FURTHER READINGS

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1. *Fundamentals of Data Structures in C++* by E.Horowitz, Sahni and D.Mehta; Galgotia Publications.
2. *Data Structures and Program Design in C* by Kruse, C.L.Tonodo and B.Leung; Pearson Education.

### Reference websites

<http://www.csee.umbc.edu>  
<http://www.cse.ucsc.edu>  
<http://www.webopedia.com>

# UNIT 7 ADVANCED TREES

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## 7.0 INTRODUCTION

Linked list representations have great advantages of flexibility over the contiguous representation of data structures. But, they have few disadvantages also. Data structures organised as trees have a wide range of advantages in various applications and it is best suited for the problems related to information retrieval.

These data structures allow the searching, insertion and deletion of node in the ordered list to be achieved in the minimum amount of time.

The data structures that we discuss primarily in this unit are Binary Search Trees, AVL trees and B-Trees. We cover only fundamentals of these data structures in this unit. Some of these trees are special cases of other trees and Trees are having a large number of applications in real life.

## 7.1 OBJECTIVES

After going through this unit, you should be able to

- know the fundamentals of Binary Search trees;
- perform different operations on the Binary Search Trees;
- understand the concept of AVL trees;

- understand the concept of B-trees, and
- perform various operations on B-trees.

## 7.2 BINARY SEARCH TREES

A Binary Search Tree is a binary tree that is either empty or a node containing a key value, left child and right child.

By analysing the above definition, we note that BST comes in two variants namely empty BST and non-empty BST.

The empty BST has no further structure, while the non-empty BST has three components.

The non-empty BST satisfies the following conditions:

- a) The key in the left child of a node (if exists) is less than the key in its parentnode.
- b) The key in the right child of a node (if exists) is greater than the key in its parent node.
- c) The left and right subtrees of the root are again binary search trees.

The following are some of the operations that can be performed on Binary searchtrees:

- Creation of an empty tree
- Traversing the BST
- Counting internal nodes (non-leaf nodes)
- Counting external nodes (leaf nodes)
- Counting total number of nodes
- Finding the height of tree
- Insertion of a new node
- Searching for an element
- Finding smallest element
- Finding largest element
- Deletion of a node.

### 7.2.1 Traversing a Binary Search Tree

Binary Search Tree allows three types of traversals through its nodes. They are as follow:

1. Pre Order Traversal
2. In Order Traversal
3. Post Order Traversal

In Pre Order Traversal, we perform the following three operations:

1. Visit the node
2. Traverse the left subtree in preorder

3. Traverse the right subtree in preorder

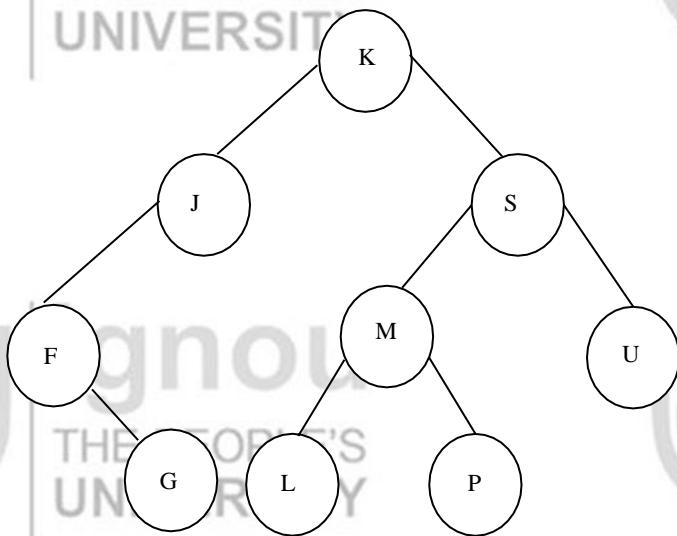
In Order Traversal, we perform the following three operations:

1. Traverse the left subtree in inorder
2. Visit the root
3. Traverse the right subtree in inorder.

In Post Order Traversal, we perform the following three operations:

1. Traverse the left subtree in postorder
2. Traverse the right subtree in postorder
3. Visit the root

Consider the BST of *Figure 7.1*



**Figure 7.1: A Binary Search Tree(BST)**

The following are the results of traversing the BST of *Figure 7.1*:

Preorder : K J F G S M L P U

Inorder : F G J K L M P S U

Postorder: G F J L P M U S K

### 7.2.2 Insertion of a node into a Binary Search Tree

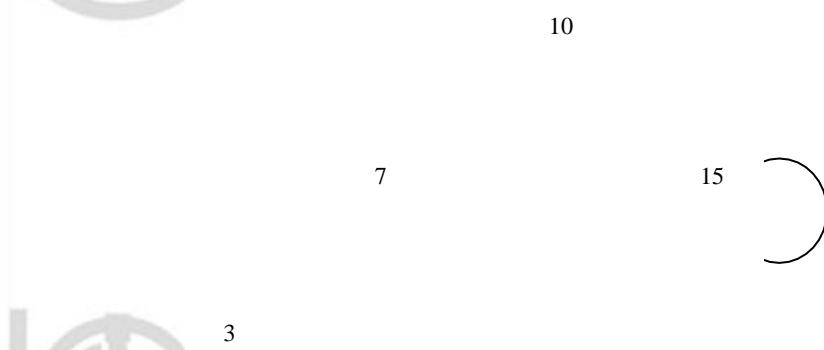
A binary search tree is constructed by the repeated insertion of new nodes into a binary tree structure.

Insertion must maintain the order of the tree. The value to the left of a given node must be less than that node and value to the right must be greater.

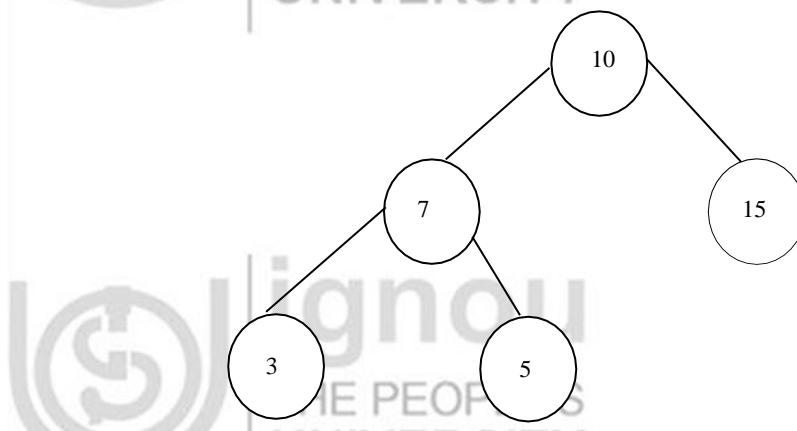
In inserting a new node, the following two tasks are performed :

- Tree is searched to determine where the node is to be inserted.
- On completion of search, the node is inserted into the tree

**Example:** Consider the BST of *Figure 7.2*. After insertion of a new node consisting of value 5, the BST of *Figure 7.3* results.



**Figure 7.2: A non-empty BST**



**Figure 7.3: Figure 7.2 after insertion of 5**

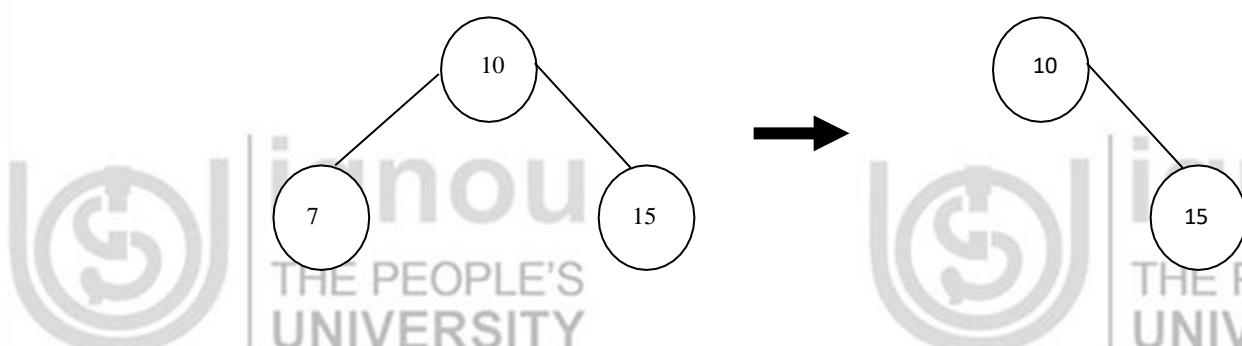
### 7.2.3 Deletion of a node from a Binary Search Tree

The algorithm to delete a node with key from a binary search tree is not simple where as many cases needs to be considered.

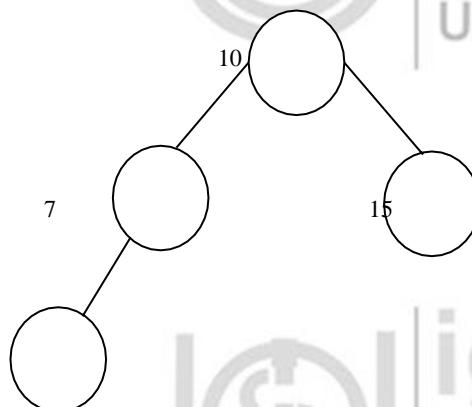
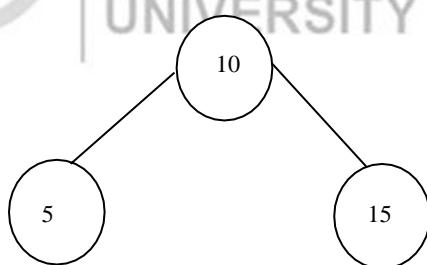
- If the node to be deleted has no sons, then it may be deleted without further adjustment to the tree.
- If the node to be deleted has only one subtree, then its only son can be moved up to take its place.
- The node  $p$  to be deleted has two subtrees, then its inorder successor  $s$  must take its place. The inorder successor cannot have a left subtree. Thus, the right son of  $s$  can be moved up to take the place of  $s$ .

**Example:** Consider the following cases in which node 5 needs to be deleted.

1. The node to be deleted has no children.



2. The node has one child

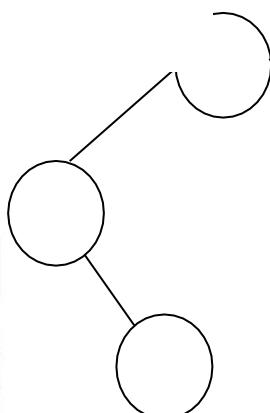


3. The node to be deleted has two children. This case is complex. The order of the binary tree must be kept intact.

### Check Your Progress 1

- 1) What are the different ways of traversing a Binary Search Tree?

- 2) What are the major features of a Binary Search Tree?




---

### 7.3 AVL TREES

---

An AVL tree is a binary search tree which has the following properties:

- The sub-tree of every node differs in height by at most one.
- Every sub tree is an AVL tree.

*Figure 7.4 depicts an AVL tree.*



Figure 7.4 : Balance requirement for an AVL tree: the left and right subtree differ by atmost one in height

AVL stands for the names of G.M. Adelson – Velskii and E.M. Landis, two Russian mathematicians, who came up with this method of keeping the tree balanced.

An AVL tree is a binary search tree which has the balance property and in addition to its key, each node stores an extra piece of information: the current balance of its subtree. The three possibilities are:

- ▶ Left – HIGH (balance factor -1)  
The left child has a height that is greater than the right child by 1.
- ▶ BALANCED (balance factor 0) Both children have the same height
- ▶ RIGHT – HIGH (balance factor +1)  
The right child has a height that is greater by 1.

An AVL tree which remains balanced guarantees  $O(\log n)$  search time, even in the worst case. Here,  $n$  is the number of nodes. The AVL data structure achieves this property by placing restrictions on the difference in heights between the sub-trees of a given node and rebalancing the tree even if it violates these restrictions.

### 7.3.1 Insertion of a node into an AVL tree

Nodes are initially inserted into an AVL tree in the same manner as an ordinary binary search tree.

However, the insertion algorithm for an AVL tree travels back along the path it took to find the point of insertion and checks the balance at each node on the path.

If a node is found that is unbalanced (if it has a balance factor of either -2 or +2) then rotation is performed, based on the inserted node's position relative to the node being examined (the unbalanced node).

### 7.3.2 Deletion of a node from an AVL tree

The deletion algorithm for AVL trees is a little more complex as there are several extra steps involved in the deletion of a node. If the node is not a leaf node, then it has at least one child. Then the node must be swapped with either its in-order successor or predecessor. Once the node has been swapped, we can delete it.

If a deletion node was originally a leaf node, then it can simply be removed.

As done in insertion, we traverse back up the path to the root node, checking the balance of all nodes along the path. If unbalanced, then the respective node is found and an appropriate rotation is performed to balance that node.

### 7.3.3 AVL tree rotations

AVL trees and the nodes it contains must meet strict balance requirements to maintain  $O(\log n)$  search time. These balance restrictions are maintained using various rotation functions.

The four possible rotations that can be performed on an unbalanced AVL tree are given below. The before and after status of an AVL tree requiring the rotation are shown (refer to *Figures 7.5, 7.6, 7.7 and 7.8*).

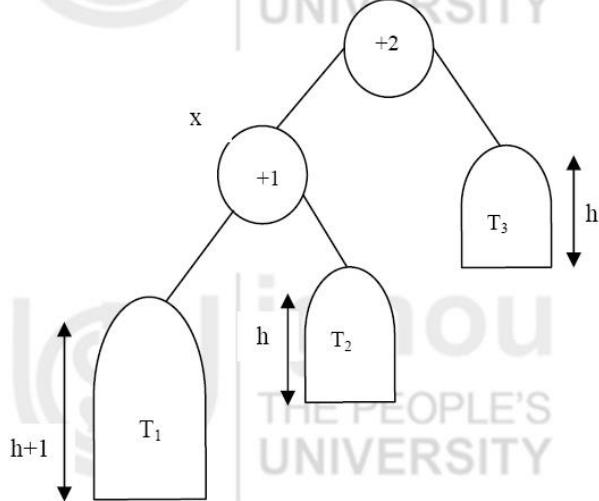


Figure 7.5: LL Rotation

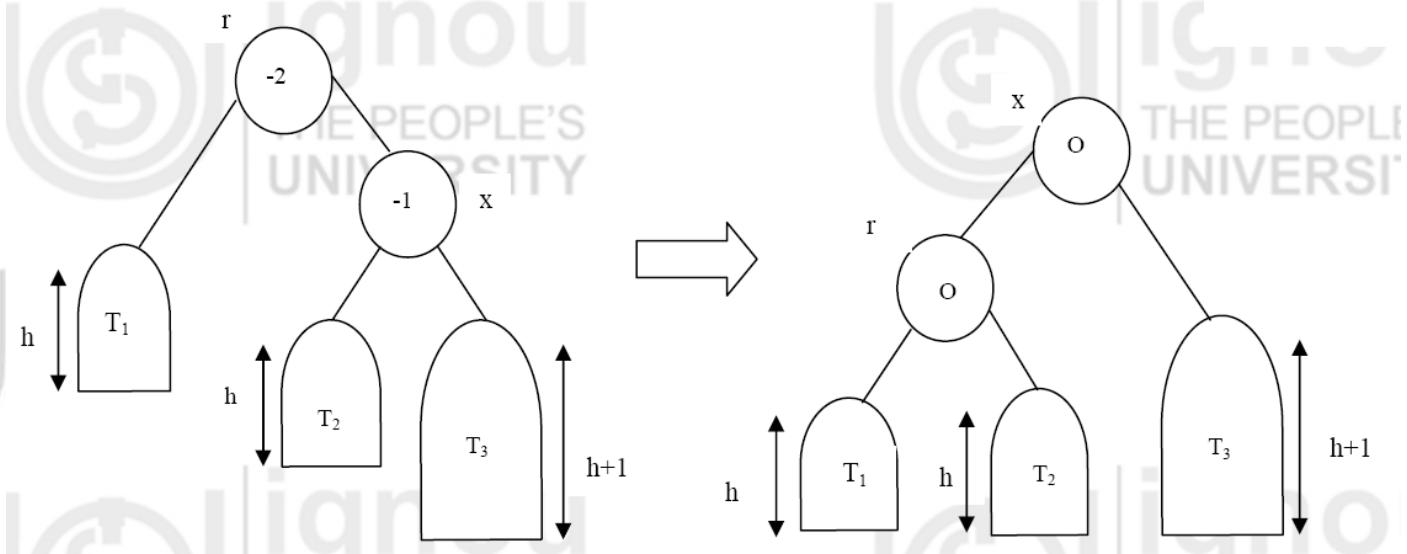


Figure: 7.6 RR Rotati

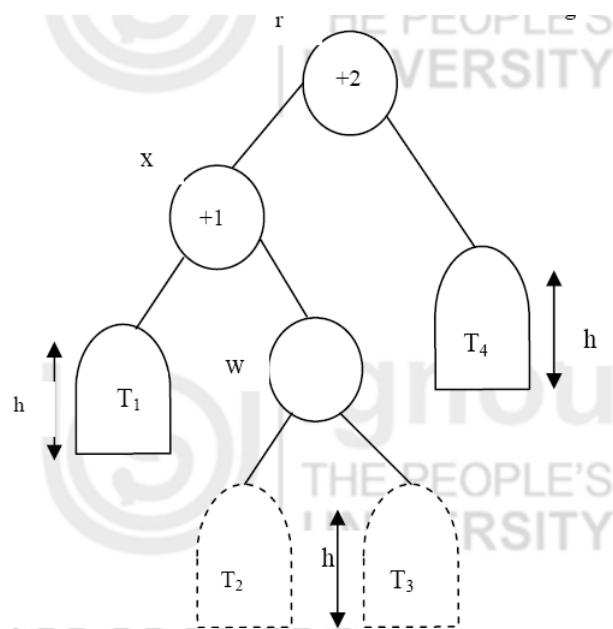


Figure 7.7: LR Rotation

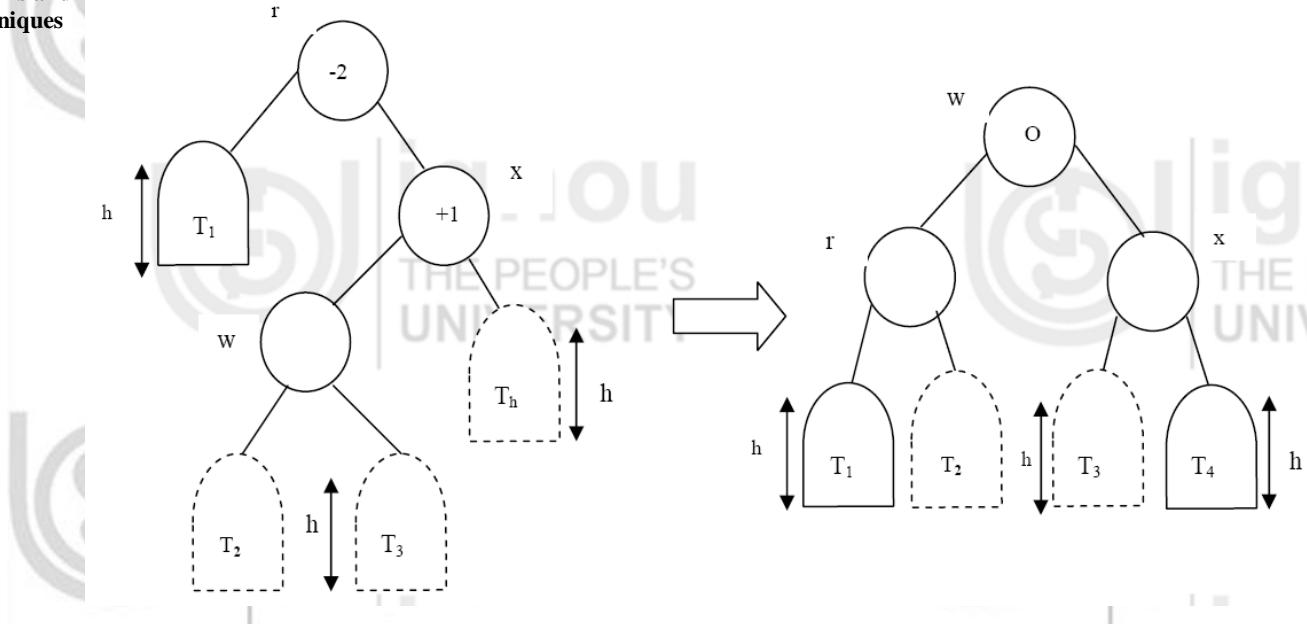


Figure 7.8: RL Rotation

**Example:** ( Single rotation in AVL tree, when a new node is inserted into the AVL tree (LL Rotation)) (refer to Figure 7.9).

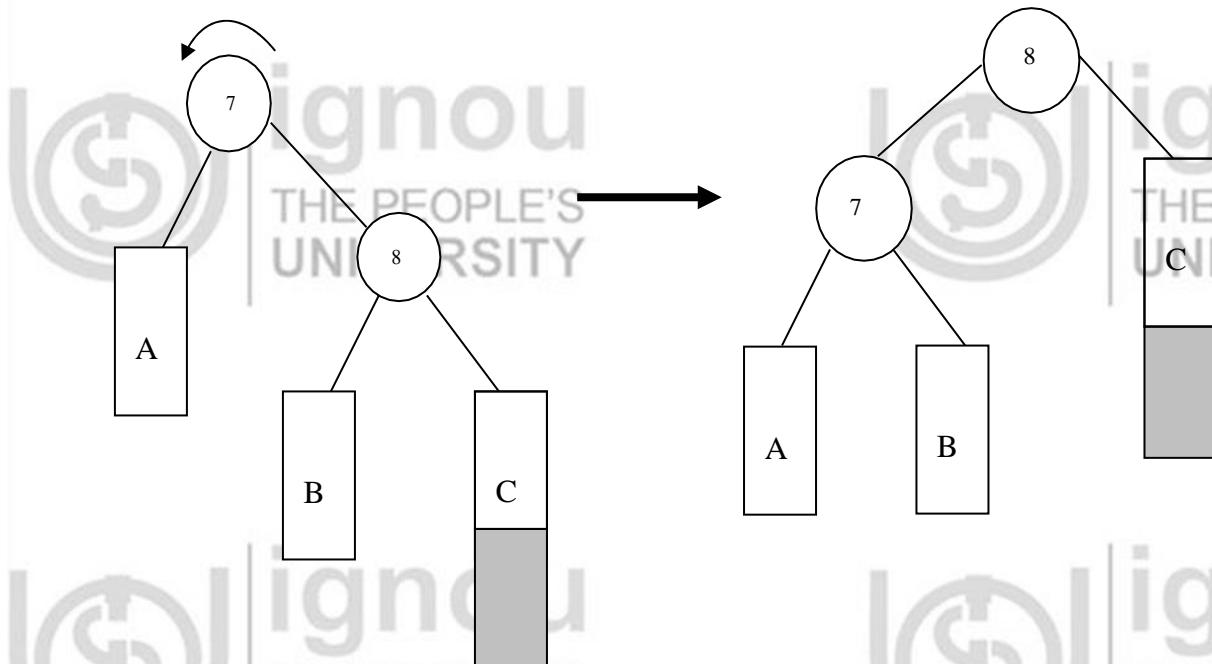


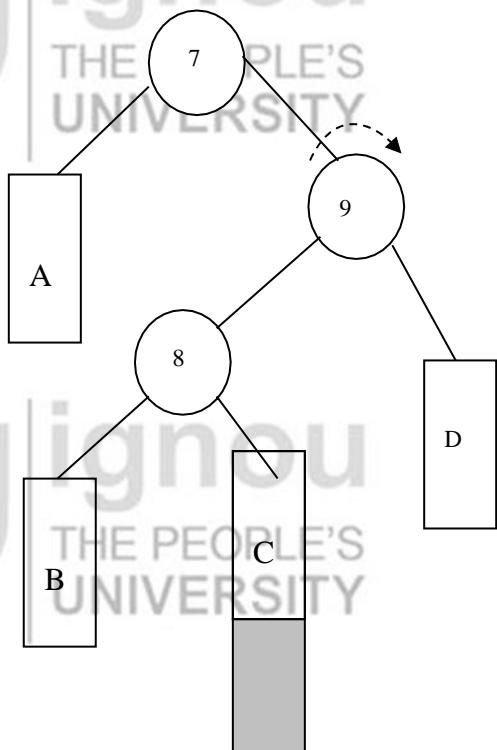
Figure 7.9: LL Rotation

The rectangles marked A, B and C are trees of equal height. The shaded rectangle stands for a new insertion in the tree C. Before the insertion, the tree was balanced, for the right child was taller than the left child by one.

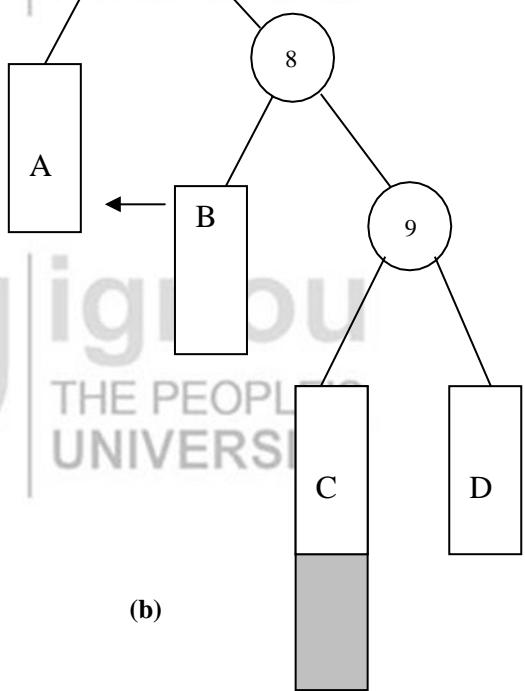
The balance was broken when we inserted a node into the right child of 7, since the difference in height became 7.

To fix the balance we make 8 the new root, make c the right child move the old root (7) down to the left together with its left subtree A and finally move subtree B across and make it the new right child of 7.

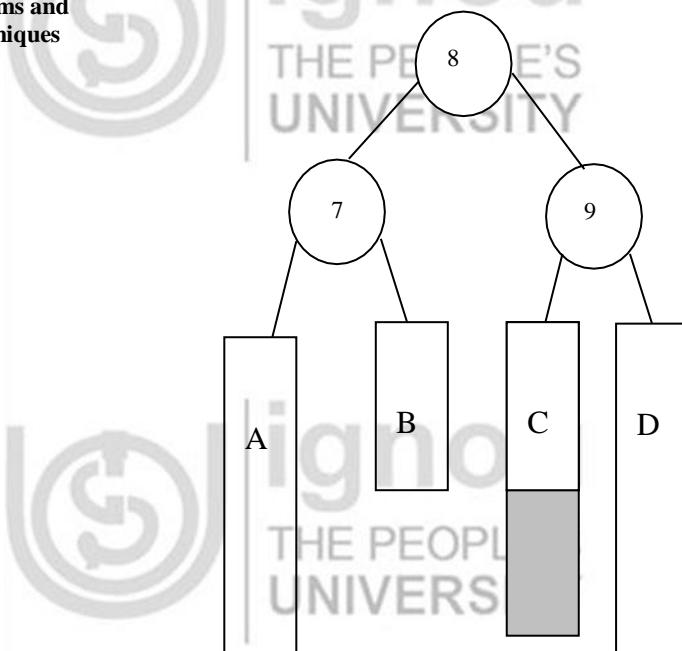
**Example:** (Double left rotation when a new node is inserted into the AVL tree (RL rotation)) (refer to Figure 7.10 ( a),(b),(c)).



(a)



(b)



(c)

**Figure 7.10: Double left rotation when a new node is inserted into the AVL tree**

A node was inserted into the subtree C, making the tree off balance by 2 at the root. We first make a right rotation around the node 9, placing the C subtree into the left child of 9.

Then a left rotation around the root brings node 9 (together with its children) up a level and subtree A is pushed down a level (together with node 7). As a result we get correct AVL tree equal balance.

An AVL tree can be represented by the following structure:

```
struct avl {
    struct node *left;
    int info;
    int bf;
    struct node *right;
};
```

*bf* is the balance factor, *info* is the value in the node.

### 7.3.4 Applications of AVL Trees

AVL trees are applied in the following situations:

- There are few insertion and deletion operations
- Short search time is needed
- Input data is sorted or nearly sorted

AVL tree structures can be used in situations which require fast searching. But, the large cost of rebalancing may limit the usefulness.

Consider the following:

1. A classic problem in computer science is how to store information dynamically so as to allow for quick look up. This searching problem arises often in dictionaries, telephone directory, symbol tables for compilers and while storing business records etc. The records are stored in a balanced binary tree, based on the keys (alphabetical or numerical) order. The balanced nature of the tree limits its height to  $O(\log n)$ , where  $n$  is the number of inserted records.
2. AVL trees are very fast on searches and replacements. But, have a moderately high cost for addition and deletion. If application does a lot more searches and replacements than it does addition and deletions, the balanced (AVL) binary tree is a good choice for a data structure.
3. AVL tree also has applications in file systems.

### Check Your Progress 2

- 1) Define the structure of an AVL tree.
- .....
- .....

## 7.4 B – TREES

B-trees are special m-ary balanced trees used in databases because their structure allows records to be inserted, deleted and retrieved with guaranteed worst case performance.

A B-Tree is a specialised multiway tree. In a B-Tree each node may contain a large number of keys. The number of subtrees of each node may also be large. A B-Tree is designed to branch out in this large number of directions and to contain a lot of keys in each node so that height of the tree is relatively small.

This means that only a small number of nodes must be read from disk to retrieve an item.

A B-Tree of order m is multiway search tree of order m such that

- All leaves are on the bottom level
- All internal nodes (except root node) have atleast  $m/2$  (non empty) children
- The root node can have as few as 2 children if it is an internal node and can have no children if the root node is a leaf node
- Each leaf node must contain atleast  $(m/2) - 1$  keys.

The following is the structure for a B-tree :struct btree

```
{
    int count;           // number of keys stored in the current node
    item_type key[3];   // array to hold 3 keys
    long branch [4];   // array of fake pointers (records numbers)
};
```

Figure 7.11 depicts a B-tree of order 5.

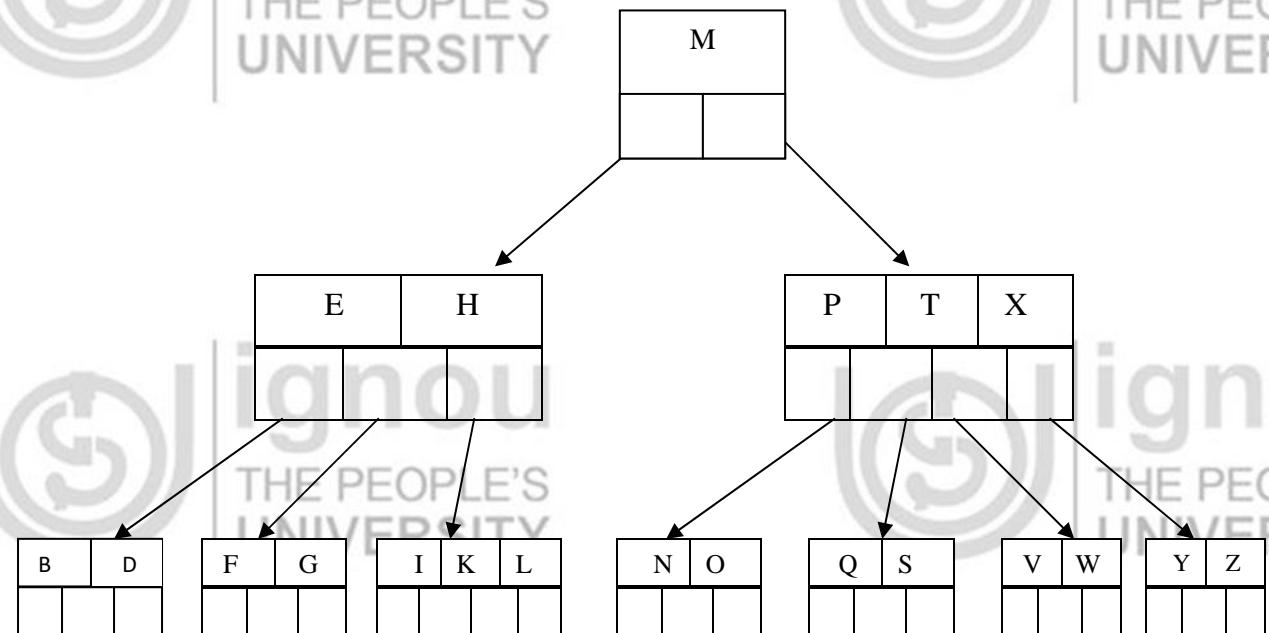


Figure 7.11: A B-tree of order 5

#### 7.4.1 Operations on B-Trees

The following are various operations that can be performed on B-Trees:

- Search
- Create
- Insert

B-Tree strives to minimize disk access and the nodes are usually stored on disk. All the

nodes are assumed to be stored in secondary storage rather than primary storage. All references to a given node are preceded by a read operation. Similarly, once a node is modified and it is no longer needed, it must be written out to secondary storage with write operation.

The following is the algorithm for searching a B-tree:

##### B-Tree Search ( $x, k$ )

```

 $i < - 1$ 
while  $i < n[x]$  and  $k > key_i[x]$ 
    do  $i \leftarrow i + 1$ 
if  $i \leq n[x]$  and  $k = key_1[x]$ 
    then return  $(x, i)$ 
if leaf [ $x$ ]
    then return NIL
else Disk – Read ( $c_i[x]$ )
    return B – Tree Search ( $C_i[x], k$ )
  
```

The search operation is similar to binary tree. Instead of choosing between a left and right child as in binary tree, a B-tree search must make an n-way choice.

The correct child is chosen by performing a linear search of the values in the node. After finding the value greater than or equal to desired value, the child pointer to the immediate left to that value is followed.

The exact running time of search operation depends upon the height of the tree. The following is the algorithm for the creation of a B-tree:

### B-Tree Create (T)

```
x ← Allocate-Node ()
Leaf [x] ← Truen
[x] ← 0
Disk-write (x)
root [T] ← x
```

The above mentioned algorithm creates an empty B-tree by allocating a new root that has no keys and is a leaf node.

The following is the algorithm for insertion into a B-tree:

### B-Tree Insert (T,K)

```
r ← root (T)
if n[r] = 2t - 1
then S ← Allocate-Node ()
root[T] ← S
leaf [S] ← FALSE
n[S] ← 0
C1 ← r
B-Tree-Split-Child (s, I, r)
B-Tree-Insert-Non full (s, k)
else
B - Tree-Insert-Non full (r, k)
```

To perform an insertion on B-tree, the appropriate node for the key must be located. Next, the key must be inserted into the node.

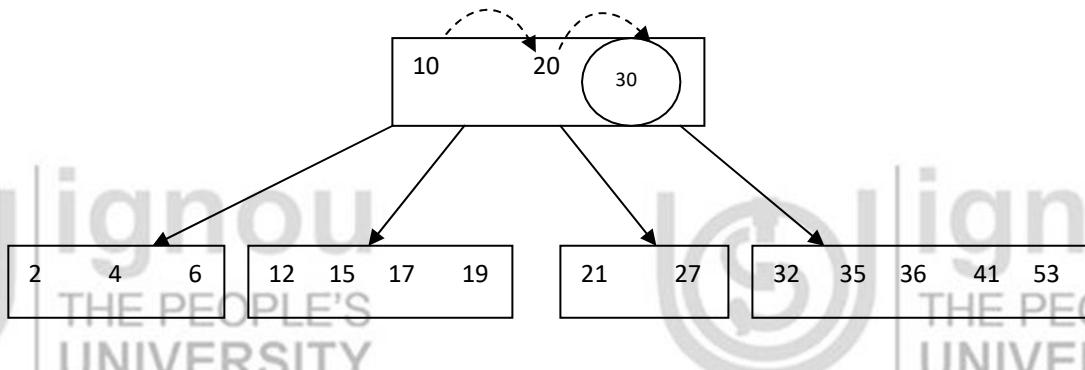
If the node is not full prior to the insertion, then no special action is required.

If node is full, then the node must be split to make room for the new key. Since splitting the node results in moving one key to the parent node, the parent node must not be full. Else, another split operation is required.

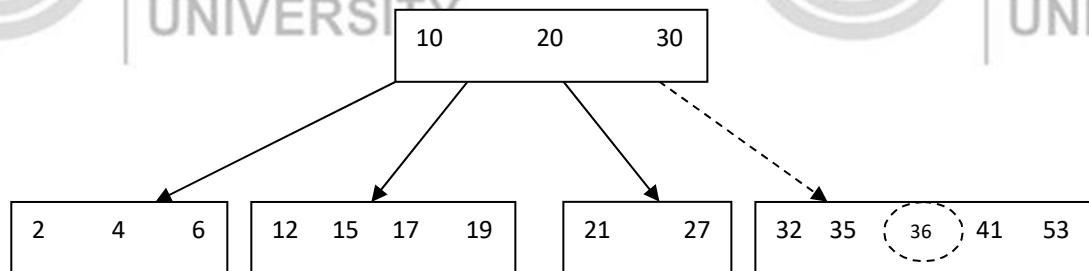
This process may repeat all the way up to the root and may require splitting the root node.

**Example:** Insertion of a key 33 into a B-Tree (w/split) (refer to *Figure 7.12*)

Step 1: Search first node for key nearest to 33. Key 30 was found.



Step 2: Node pointed by key 30, is searched for inserting 33. Node is shifted upwards.



Step 3: Key 33 is inserted between 32 and 35.

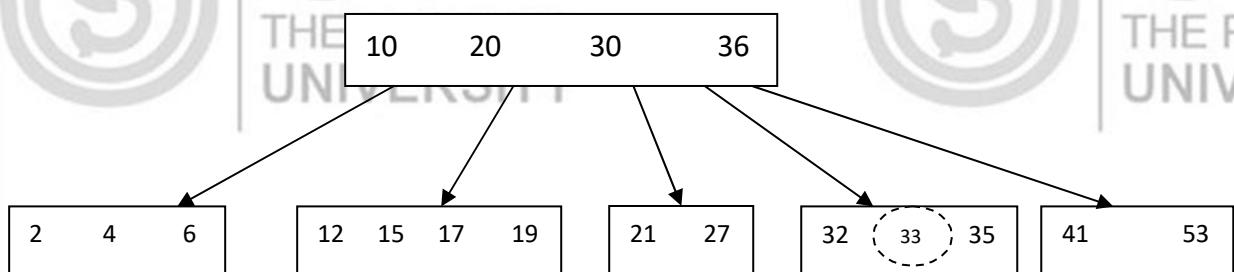
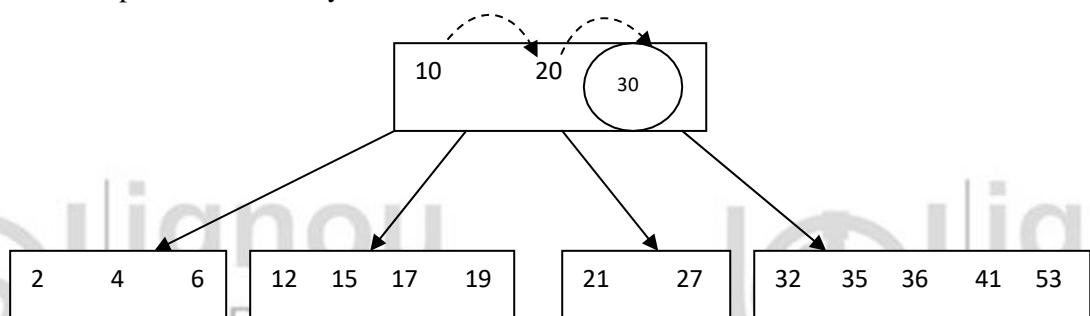


Figure 7.12 : A B-tree

Deletion of a key from B-tree is possible, but care must be taken to ensure that the properties of b-tree are maintained if the deletion reduces the number of keys in a node below the minimum degree of tree, this violation must be corrected by combining several nodes and possibly reducing the height of the tree. If the key has children, the children must be rearranged.

**Example (Searching of a B – Tree for key 21(refer to Figure 7.13))**

Step 1: Search for key 21 in first node. 21 is between 20 and 30.



Step2 : Searching is conducted on the nodes connected by 30.

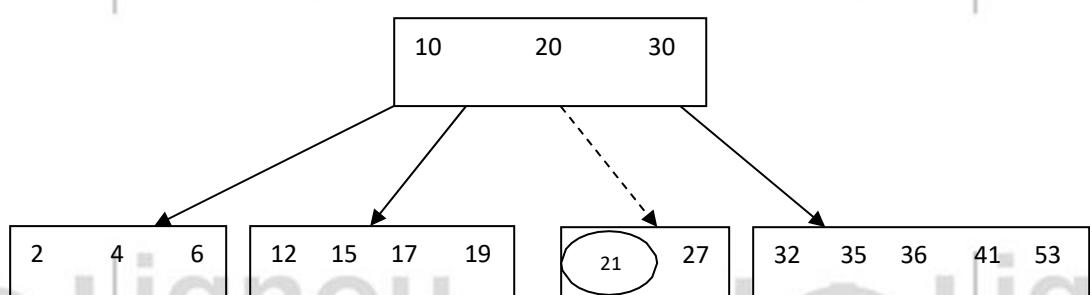


Figure 7.13 : A B-tree

### 7.4.2 Applications of B-trees

A database is a collection of data organised in a fashion that facilitates updation, retrieval and management of the data. Searching an unindexed database containing  $n$  keys will have a worst case running time of  $O(n)$ . If the same data is indexed with a b-tree, then the same search operation will run in  $O(\log n)$  time. Indexing large amounts of data can significantly improve search performance.

#### Check Your Progress 3

- 1) Create a B – Tree of order 5 for the following:

CNGAHEKQMSWLTDPRXYS

- 2) Define a multiway tree of order  $m$ .

## 7.5 SPLAY TREES

Addition of new records in a Binary tree structure always occurs as leaf nodes, which are further away from the root node making their access slower. If this new record is to be accessed very frequently, then we cannot afford to spend much time in reaching it but would require it to be positioned close to the root node. This would call for readjustment or rebuilding of the tree to attain the desired shape. But, this process of rebuilding the tree every time as the preferences for the records change is tedious and time consuming. There must be some measure so that the tree adjusts itself automatically as the frequency of accessing the records changes. Such a self-adjusting tree is the Splay tree.

Splay trees are self-adjusting binary search trees in which every access for insertion or retrieval of a node, lifts that node all the way up to become the root, pushing the other nodes out of the way to make room for this new root of the modified tree. Hence, the frequently accessed nodes will frequently be lifted up and remain around the root position; while the most infrequently accessed nodes would move farther and farther away from the root.

This process of readjusting may at times create a highly imbalanced splay tree, wherein a single access may be extremely expensive. But over a long sequence of accesses, these expensive cases may be averaged out by the less expensive ones to produce excellent results over a long sequence of operations. The analytical tool used for this purpose is the Amortized algorithm analysis. This will be discussed in detail in the following sections.

### 7.5.1 Splaying Steps

Readjusting for tree modification calls for rotations in the binary search tree. Single rotations are possible in the left or right direction for moving a node to the root position. The task would be achieved this way, but the performance of the tree amortized over many accesses may not be good.

Instead, the key idea of splaying is to move the accessed node two levels up the tree at each step. Basic terminologies in this context are:

Zig: Movement of one step down the path to the left to fetch a node up. Zag: Movement of one step down the path to the right to fetch a node up.

With these two basic steps, the possible splay rotations are:

Zig-Zig: Movement of two steps down to the left.

Zag-Zag: Movement of two steps down to the right.

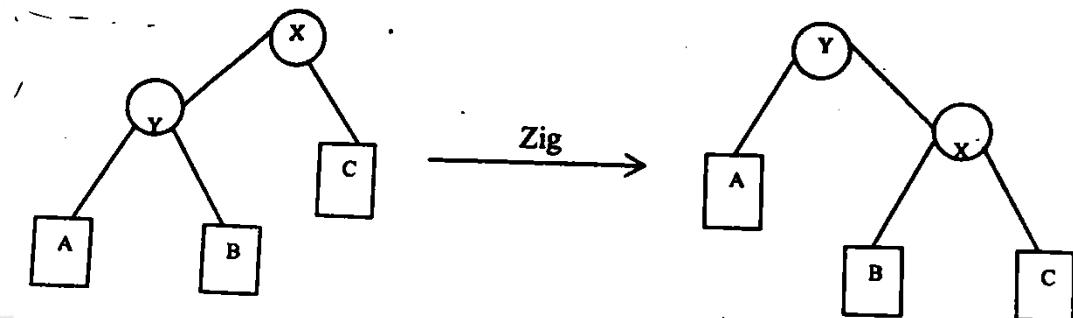
Zig-Zag: Movement of one step left and then right.

Zag-Zig: Movement of one step right and then left.

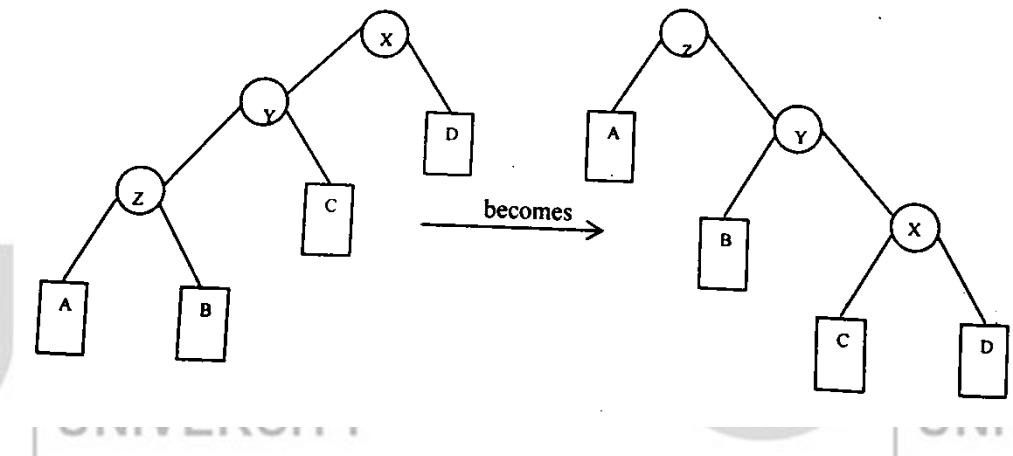
Figure 7.14 depicts the splay rotations.

Zig:

THE PEOPLE'S



Zig-Zig:



Zig-Zag:

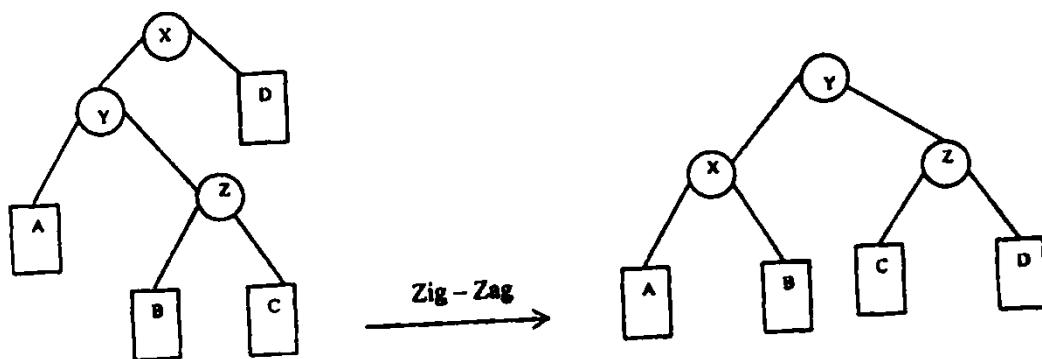


Figure 7.14: Splay rotations

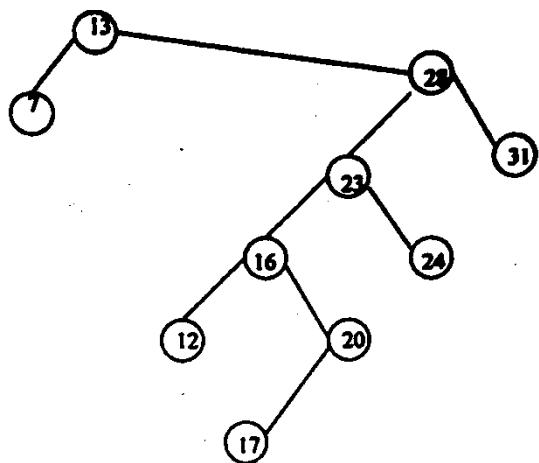
Splaying may be top-down or bottom-up. In bottom-up splaying, splaying begins at the accessed node, moving up the chain to the root. While in top-down splaying, splaying begins from the top while searching for the node to access. In the next section, we would be discussing the top-down splaying procedure:

As top-down splaying proceeds, the tree is split into three parts:

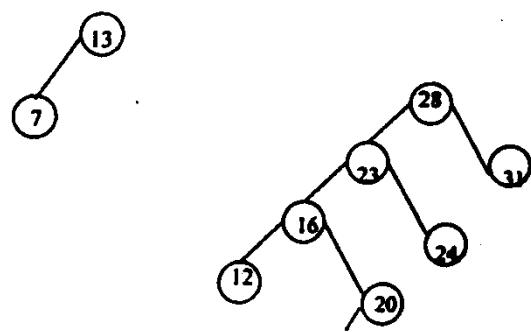
- Central SubTree:** This is initially the complete tree and may contain the target node. Search proceeds by comparison of the target value with the root and ends with the root of the central subtree being the node containing the target if present or null node if the target is not present.
- Left SubTree:** This is initially empty and is created as the central subtree is splayed. It consists of nodes with values less than the target being searched.
- Right SubTree:** This is also initially empty and is created similar to left subtree. It consists of nodes with values more than the target node.

Figure 7.15 depicts the splaying procedure with an example, attempting to splay at 20.

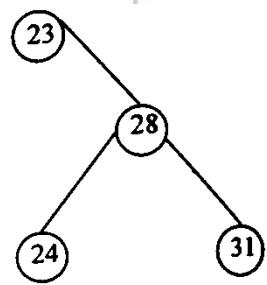
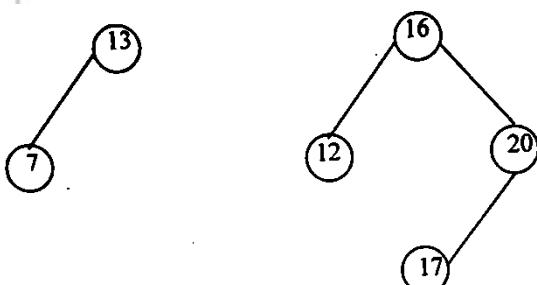
Initially,



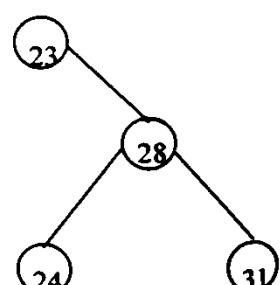
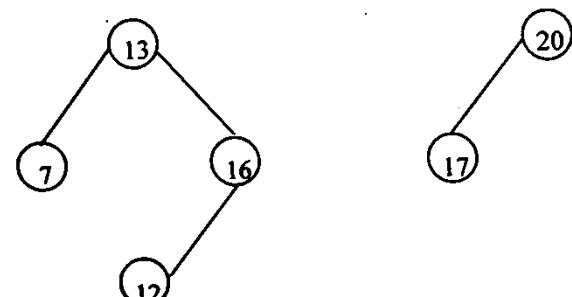
The first step is Zig-Zag:



The next step is Zig-Zig:



The next step is the terminal zig:



Finally, reassembling the three trees, we get:

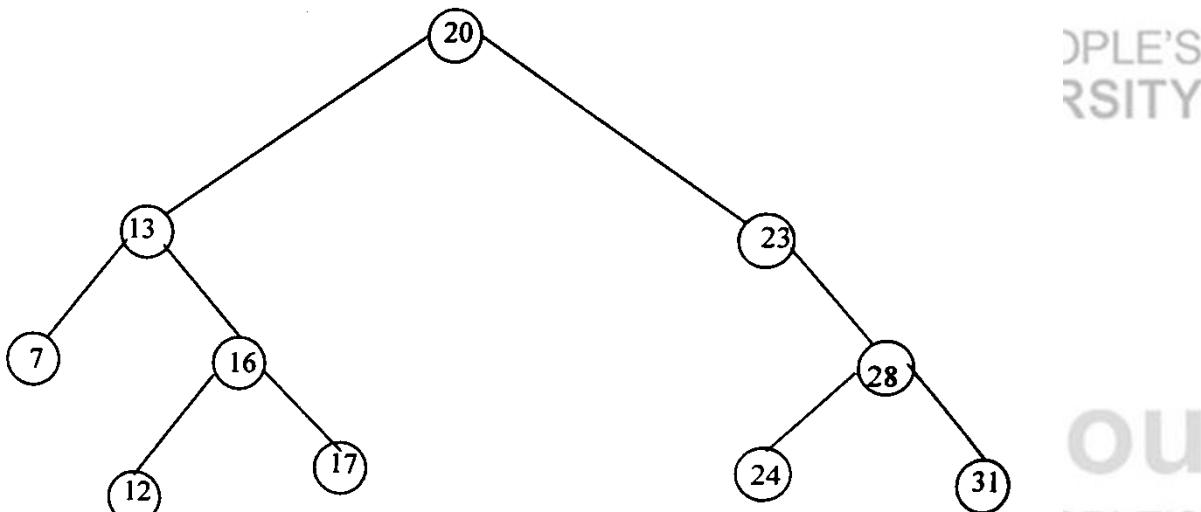


Figure 7.15: Splaying procedure

### 7.5.2 Splaying Algorithm

Insertion and deletion of a target key requires splaying of the tree. In case of insertion, the tree is splayed to find the target. If, target key is found, then we have a duplicate and the original value is maintained. But, if it is not found, then the target is inserted as the root.

In case of deletion, the target is searched by splaying the tree. Then, it is deleted from the root position and the remaining trees reassembled, if found.

Hence, splaying is used both for insertion and deletion. In the former case, to find the proper position for the target element and avoiding duplicity and in the latter case to bring the desired node to root position.

#### Splaying procedure

For splaying, three trees are maintained, the central, left and right subtrees. Initially, the central subtree is the complete tree and left and right subtrees are empty. The target key is compared to the root of the central subtree where the following two conditions are possible:

- Target > Root: If target is greater than the root, then the search will be more to the right and in the process, the root and its left subtree are shifted to the left tree.
- Target < Root: If the target is less than the root, then the search is shifted to the left, moving the root and its right subtree to right tree.

We repeat the comparison process till either of the following conditions are satisfied:

- Target is found: In this, insertion would create a duplicate node. Hence, original node is maintained. Deletion would lead to removing the root node.
- Target is not found and we reach a null node: In this case, target is inserted in the null node position.

Now, the tree is reassembled. For the target node, which is the new root of our tree, the largest node is the left subtree and is connected to its left child and the smallest node

in the right subtree is connected as its right child.

## Amortized Algorithm Analysis

In the amortized analysis, the time required to perform a set of operations is the average of all operations performed. Amortized analysis considers a long sequence of operations instead of just one and then gives a worst-case estimate. There are three different methods by which the amortized cost can be calculated and can be differentiated from the actual cost. The three methods, namely, are:

- Aggregate analysis: It finds the average cost of each operation. That is,  $T(n)/n$ . The amortized cost is same for all operations.
- Accounting method: The amortized cost is different for all operations and charges a credit as prepaid credit on some operations.
- Potential method: It also has different amortized cost for each operation and charges a credit as the potential energy to other operations.

There are different operations such as stack operations (push, pop, multipop) and an increment which can be considered as examples to examine the above three methods.

Every operation on a splay tree and all splay tree operations take  $O(\log n)$  amortized time.

## 7.6 RED-BLACK TREES

A Red-Black Tree (RBT) is a type of Binary Search tree with one extra bit of storage per node, i.e. its color which can either be red or black. Now the nodes can have any of the color (red, black) from root to a leaf node. These trees are such that they guarantee  $O(\log n)$  time in the worst case for searching.

Each node of a red black tree contains the field color, key, left, right and p (parent). If a child or a parent node does not exist, then the pointer field of that node contains NULL value.

### 7.6.1 Properties of a Red-Black Tree

Any binary search tree should contain following properties to be called as a red-black tree.

1. Each node of a tree should be either red or black.
2. The root node is always black.
3. If a node is red, then its children should be black.
4. For every node, all the paths from a node to its leaves contain the same number of black nodes.

We define the number of black nodes on any path from but not including a node  $x$  down to a leaf, the black height of the node is denoted by  $bh(x)$ .

Figure 7.16 depicts a Red-Black Tree.

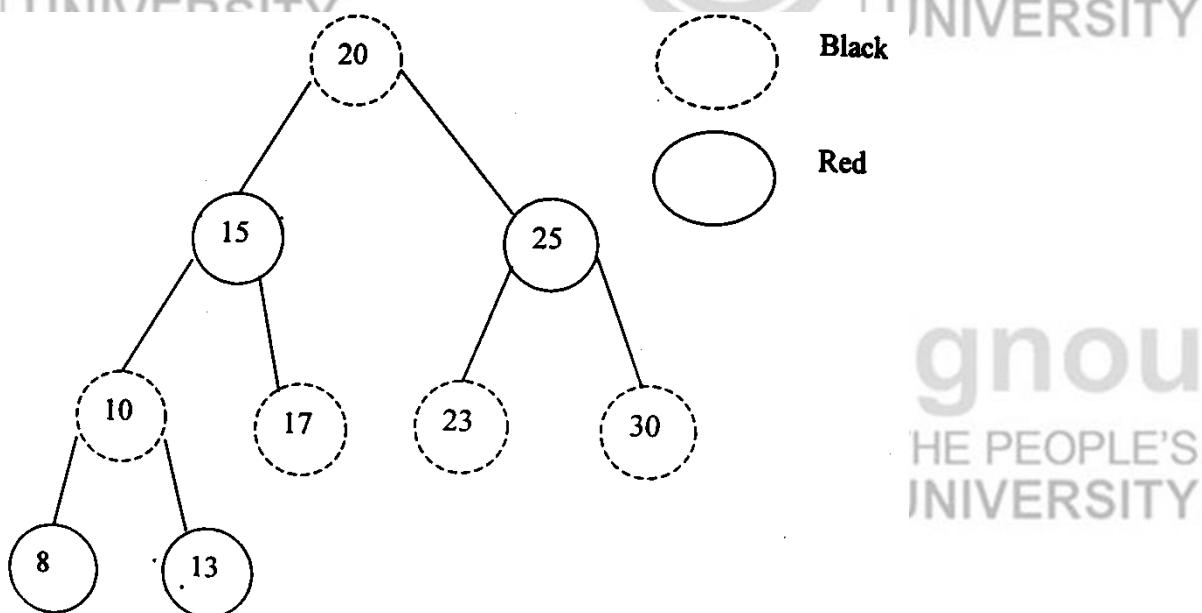


Figure 7.16: A Red-Black tree

Red-black trees contain two main operations, namely INSERT and DELETE. When the tree is modified, the result may violate red-black properties. To restore the tree

properties, we must change the color of the nodes as well as the pointer structure. We can change the pointer structure by using a technique called rotation which preserves inorder key ordering. There are two kinds of rotations: left rotation and right rotation (refer to Figures 7.17 and 7.18).

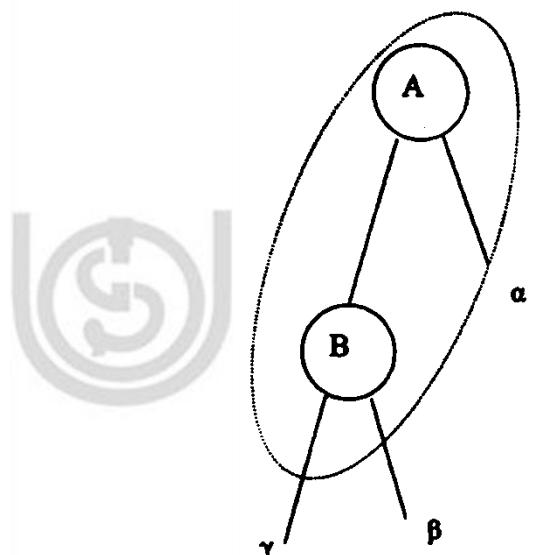


Figure 7.17: Left rotation

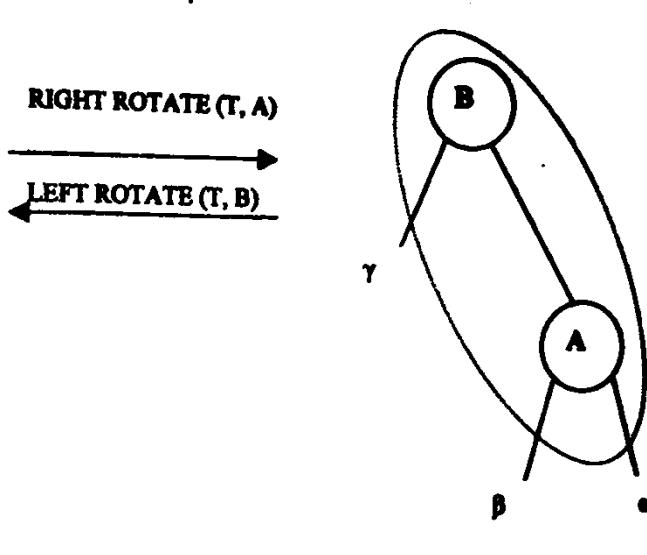


Figure 7.18: Right rotation

When we do a left rotation on a node  $y$ , we assume that its right child  $x$  is non null. The left rotation makes  $x$  as the new root of the subtree with  $y$  as  $x$ 's left child and  $x$ 's left child as  $y$ 's right child.

The same procedure is repeated vice versa for the right rotation.

### 7.6.2 Insertion into a Red-Black Tree

The insertion procedure in a red-black tree is similar to a binary search tree i.e., the insertion proceeds in a similar manner but after insertion of nodes  $x$  into the tree  $T$ , we color it red. In order to guarantee that the red-black properties are preserved, we then fix up the updated tree by changing the color of the nodes and performing rotations. Let us write the pseudo code for insertion.

The following are the two procedures followed for insertion into a Red-Black Tree:

*Procedure 1:* This is used to insert an element in a given Red-Black Tree. It involves the method of insertion used in binary search tree.

*Procedure 2:* Whenever the node is inserted in a tree, it is made red, and after insertion, there may be chances of loosing Red-Black Properties in a tree, and, so, some cases are to be considered inorder to retain those properties.

During the insertion procedure, the inserted node is always red. After inserting a node, it is necessary to notify that which of the red-black properties are violated. Let us now look at the execution of fix up. Let  $Z$  be the node which is to be inserted and is colored red. At the start of each iteration of the loop,

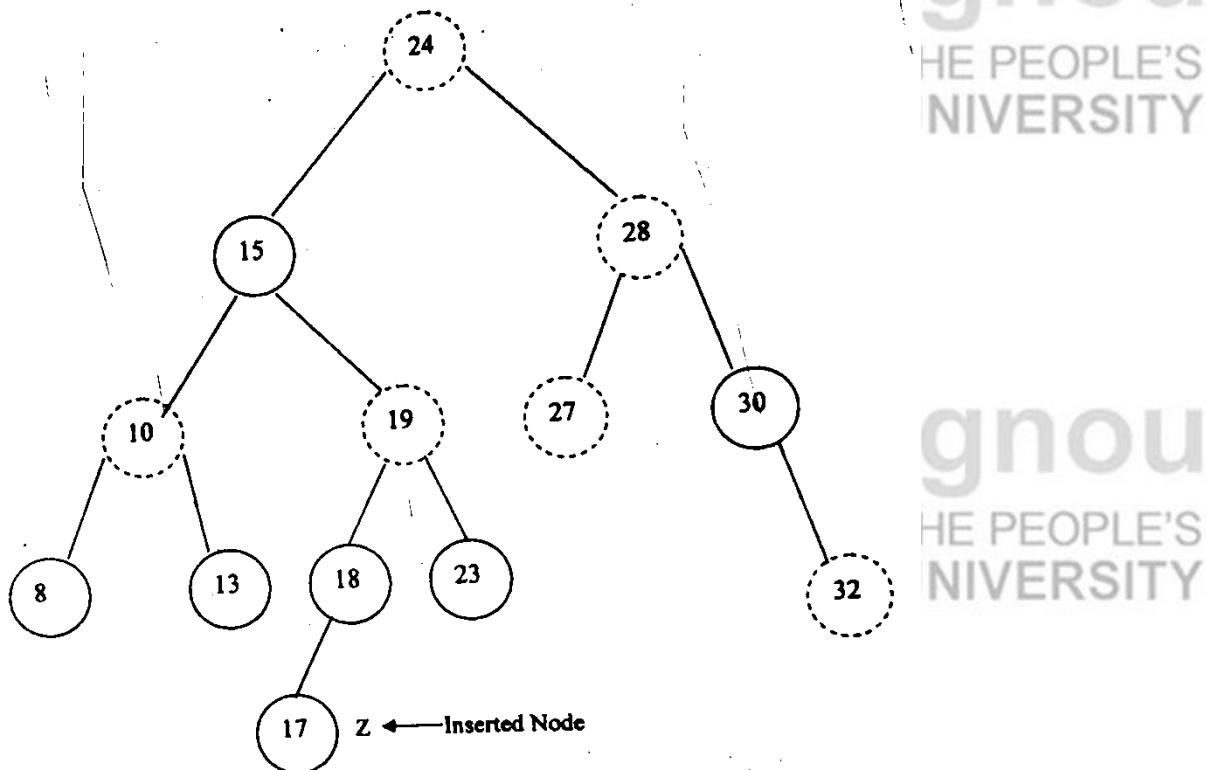
1. Node  $Z$  is red
2. If  $P(Z)$  is the root, then  $P(Z)$  is black
3. Now if any of the properties i.e. property 2 is violated if  $Z$  is the root and is red OR when property 4 is violated if both  $Z$  and  $P(Z)$  are red, then we consider 3 cases in the fix up algorithm. Let us now discuss those cases.

Case 1(Z's uncle y is red): This is executed when both parent of Z ( $P(Z)$ ) and uncle of Z, i.e. y are red in color. So, we can maintain one of the property of Red-Black tree by making both  $P(Z)$  and y black and making point of  $P(Z)$  to be red, thereby maintaining one more property. Now, this while loop is repeated again until color of y is black.

Case 2 (Z's uncle is black and Z is the right child): So, make parent of Z to be Z itself and apply left rotation to newly obtained Z.

Case 3 (Z's uncle is black and Z is the left child): This case executes by making parent of Z as black and  $P(P(Z))$  as red and then performing right rotation to it i.e., to( $P(Z)$ ).

The above 3 cases are also considered conversely when the parent of Z is to the right of its own parent. All the different cases can be seen through an example. Consider a red-black tree drawn below with a node z (17 inserted in it) (refer to *Figure 7.19*).



**Figure 7.19: A Red-Black Tree after insertion of node 17**

Before the execution of any case, we should first check the position of  $P(Z)$  i.e. if it is towards left of its parent, then the above cases will be executed but, if it is towards the right of its parent, then the above 3 cases are considered conversely.

Now, it is seen that Z is towards the left of its parent (refer to *Figure 7.20*). So, the above cases will be executed and another node called y is assigned which is the uncle of Z and now cases to be executed are as follows:

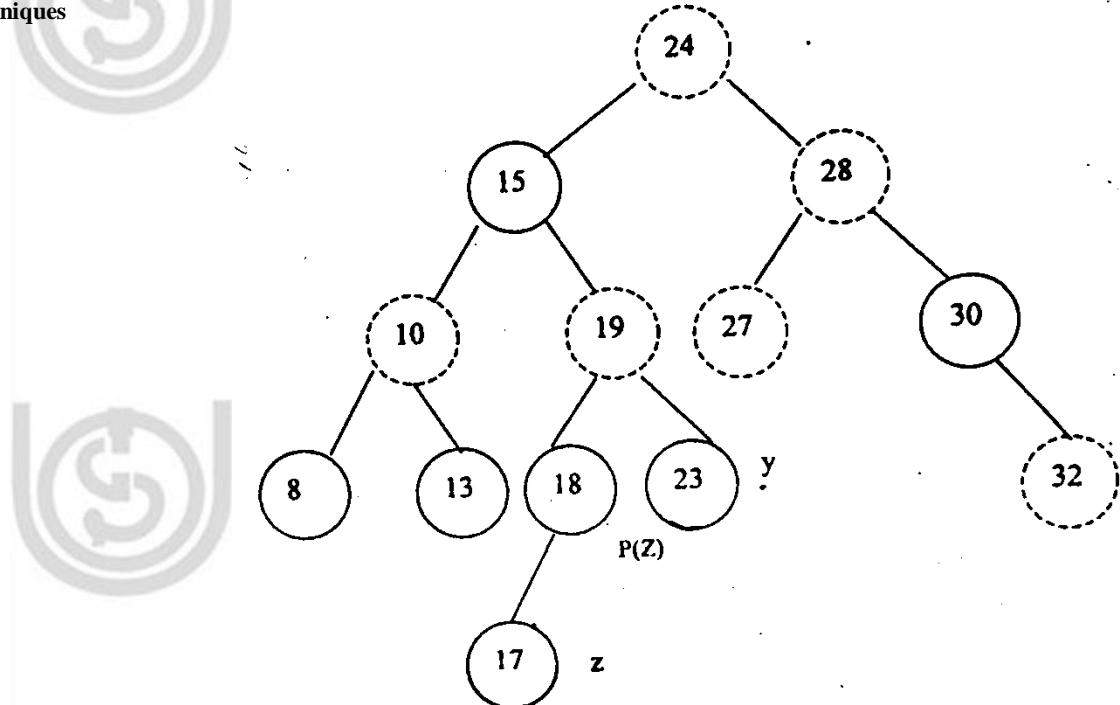


Figure 7.20: Z is to the left of its parent

Case 1: Property 4 is violated as both z and parent(z) are red (refer to *Figure 7.21*).

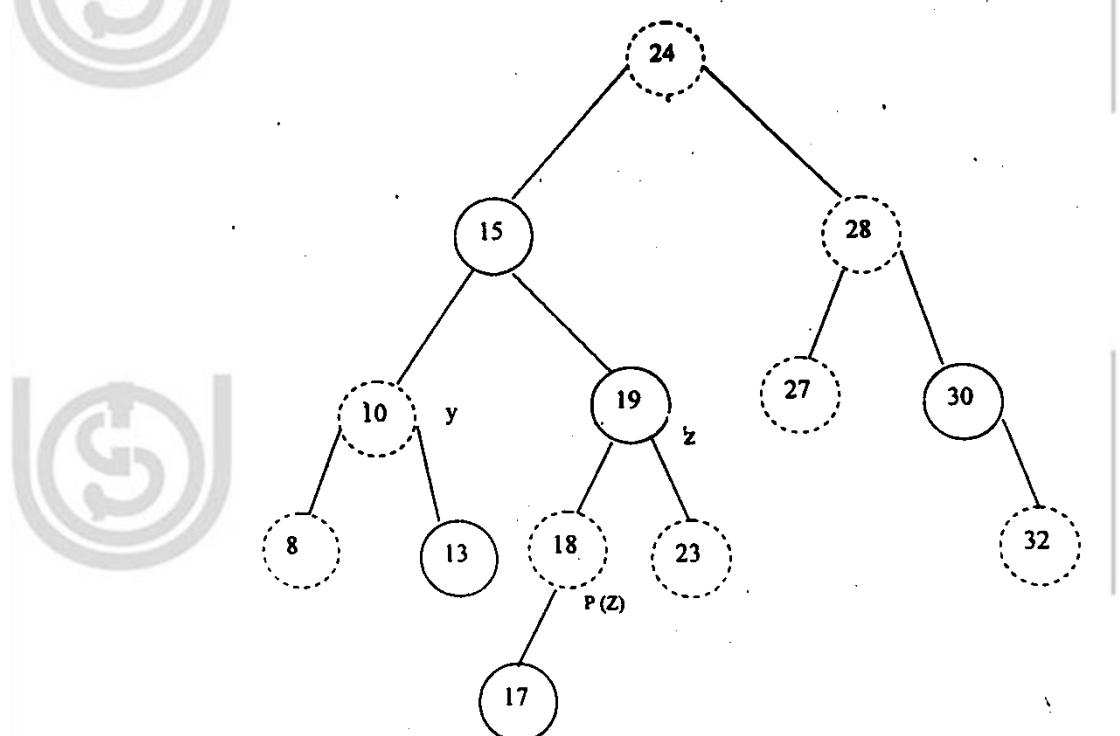
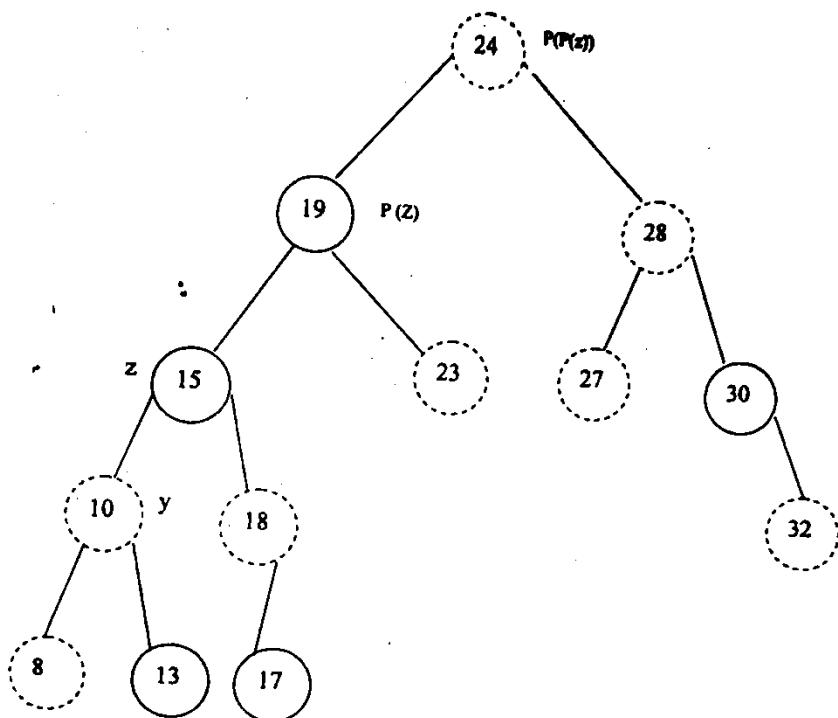


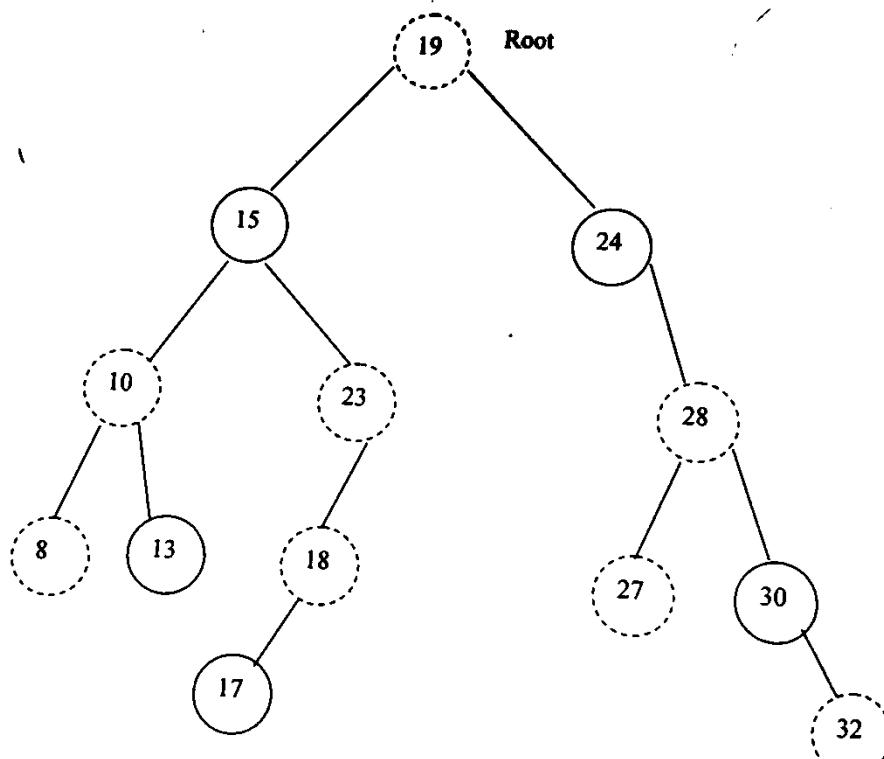
Figure 7.21: Both Z and P(Z) are red

Now, let us check to see which case is executed.



**Figure 7.22:** Result of application of case-2

Case 3: The application of this case results in *Figure 7.23*.



**Figure 7.23:** Result of application of case-3

Finally, it resulted in a perfect Red-Black Tree (Figure 7.23).

### 7.6.3 Deletion from a Red-Black Tree

Deletion in a RBT uses two main procedures, namely,

Procedure 1: This is used to delete an element in a given Red-Black Tree. It involves the method of deletion used in binary search tree.

Procedure 2: Whenever the node is deleted from a tree, and after deletion, there may be chances of losing Red-Black Properties in a tree and so, some cases are to be considered in order to retain those properties.

This procedure is called only when the successor of the node to be deleted is Black, but if y is red, the red-black properties still hold and for the following reasons:

- No red nodes have been made adjacent
- No black heights in the tree have changed
- y could not have been the root

Now, the node (say x) which takes the position of the deleted node (say z) will be called in procedure 2. Now, this procedure starts with a loop to make the extra black up to the tree until

- X points to a black node
- Rotations to be performed and recoloring to be done
- X is a pointer to the root in which the extra black can be easily removed

This while loop will be executed until x becomes root and its color is red. Here, a new node (say w) is taken which is the sibling of x.

There are four cases which we will be considering separately as follows:

#### Case 1: If color of w's sibling of x is red

Since W must have black children, we can change the colors of w and p (x) and then left rotate p (x) and the new value of w to be the right node of parent of x. Now, the conditions are satisfied and we switch over to case 2, 3 and 4.

#### Case 2: If the color of w is black and both its children are also black.

Since w is black, we make w to be red leaving x with only one black and assign parent (x) to be the new value of x. Now, the condition will be again checked, i.e. x = left (p(x)).

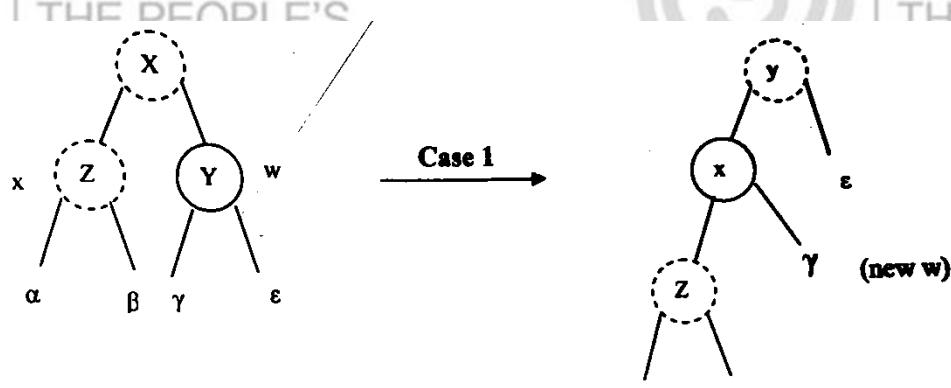


Figure 7.24: Application of case-1

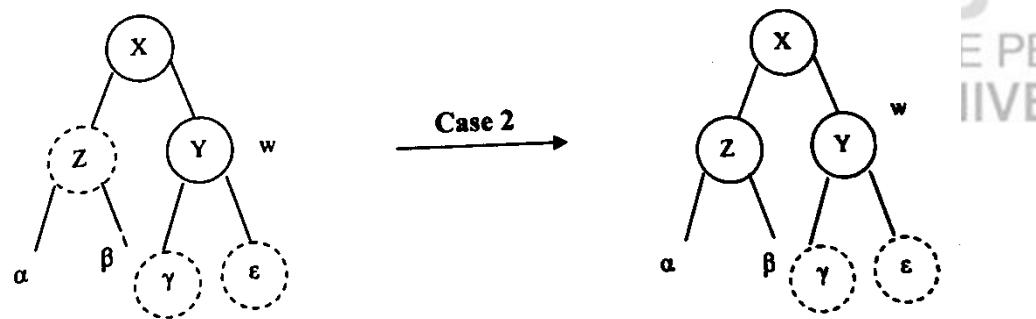


Figure 7.25: Application of case-2

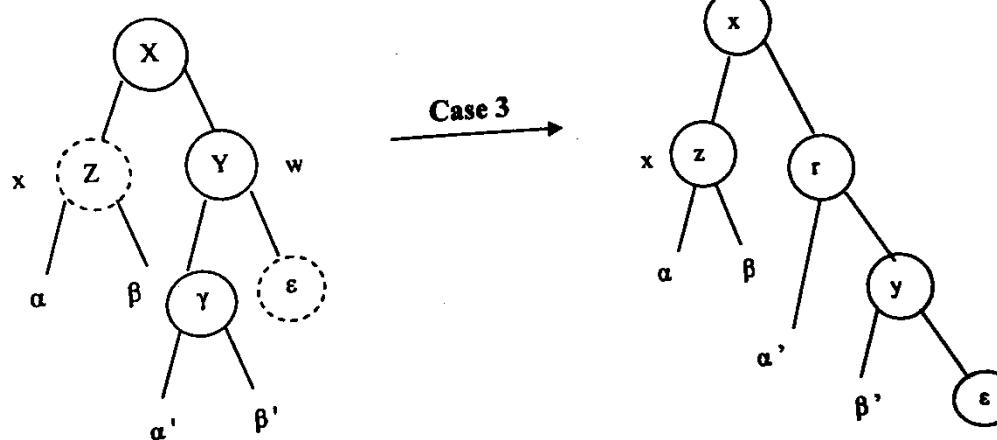


Figure 7.26: Application of case-3

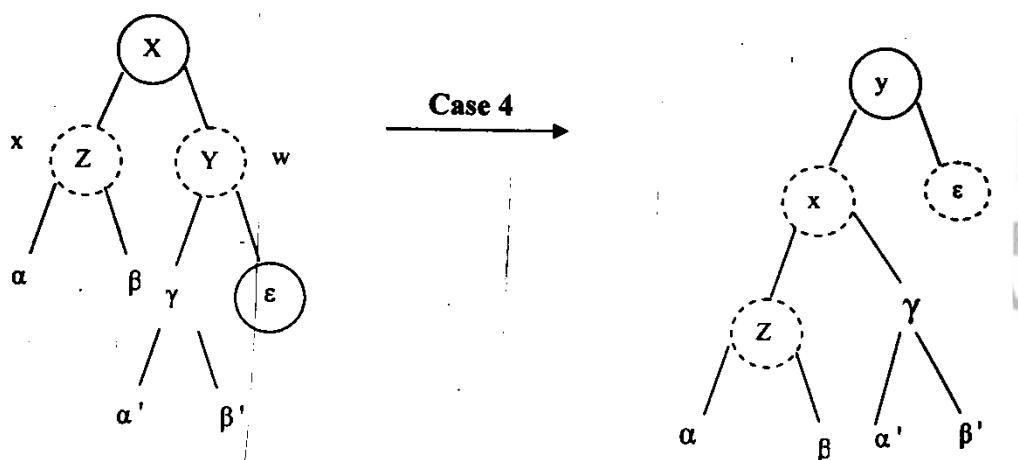


Figure 7.27: Application of case-4

**Case 3:** If the color of w is black, but its left child is red and w's right child is black.

After entering case-3, we change the color of left child of w to black and that of w to

be red and then perform right rotation on w without violating any of the black properties. The new sibling w of x is now a black node with a red right child and thus case 4 is obtained.

**Case 4:** When w is black and w's right child is red.

This can be done by making some color changes and performing a left rotation on p(x). We can remove the extra black on x, making it single black. Setting x to be the root causes the while loop to terminate.

**Note:** In the above *Figures 7.24, 7.25, 7.26 and 7.27*,  $\alpha, \alpha', \beta, \beta', \gamma, \varepsilon$  are assumed to be either red or black depending upon the situation.

## 7.7 AA-TREES

Red-Black trees have introduced a new property in the binary search tree, i.e., an extra property of color (red, black). But, as these trees grow, in their operations like insertion, deletion, it becomes difficult to retain all the properties, especially in case of deletion. Thus, a new type of binary search tree can be described which has no property of having a color, but has a new property introduced based on the color which is the information for the new. This information of the level of a node is stored in a small integer (may be 8 bits). Now, AA-trees are defined in terms of level of each node instead of storing a color bit with each node. A red-black tree used to have various conditions to be satisfied regarding its color and AA-trees have also been designed in such a way that it should satisfy certain conditions regarding its new property, i.e., level.

The level of a node will be as follows:

1. Same of its parent, if the node is red.
2. One if the node is a leaf.
3. Level will be one less than the level of its parent, if the node is black.

Any red-black tree can be converted into an AA-tree by translating its color structure to levels such that left child is always one level lower than its parent and right child is always same or at one level lower than its parent. When the right child is at same level to its parent, then a horizontal link is established between them. Thus, we conclude that it is necessary that horizontal links are always at the right side and that there may not be two consecutive links. Taking into consideration of all the above properties, we show a AA-tree as follows (refer to *Figure 7.28*).

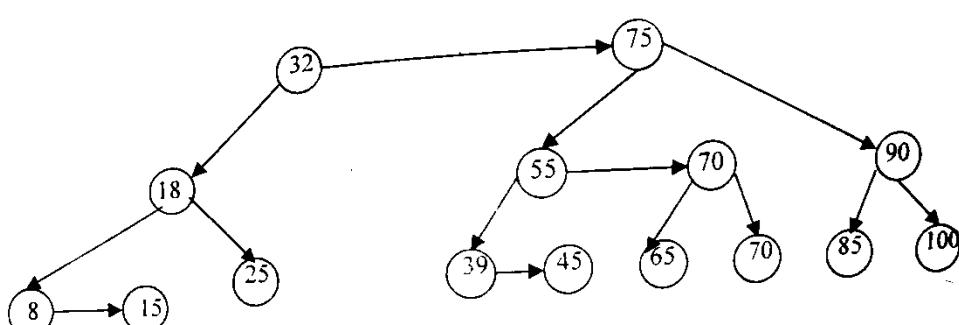


Figure 7.28: AA-tree

After having a look at the AA-tree above, we now look at different operations that can be performed at such trees.

The following are various operations on a AA-tree:

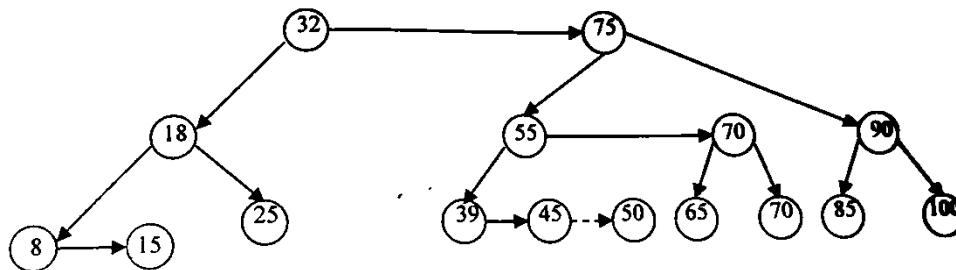
1. Searching: Searching is done by using an algorithm that is similar to the search algorithm of a binary search tree.
2. Insertion: The insertion procedure always start from the bottom level. But, while performing this function, either of the two problems can occur:

- (a) Two consecutive horizontal links (right side)
- (b) Left horizontal link.

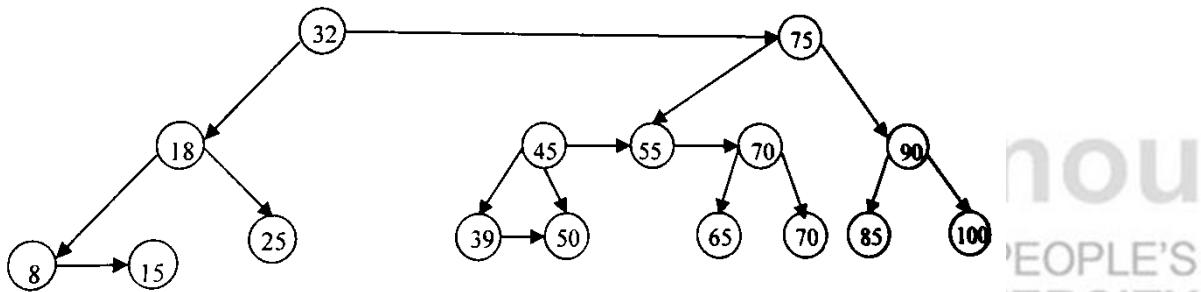
While studying the properties of AA-tree, we said that conditions (a) and (b) should not be satisfied. Thus, in order to remove conditions (a) and (b), we use two new functions namely `skew()` and `split()` based on the rotations of the node, so that all the properties of AA-trees are retained.

The condition that (a) two consecutive horizontal links in an AA-tree can be removed by a left rotation by `split()` whereas the condition (b) can be removed by right rotations through function `skew()`. Either of these functions can remove these condition, but can also arise the other condition. Let us demonstrate it with an example. Suppose, in the AA-tree of *Figure 7.28*, we have to insert node 50.

According to the condition, the node 50 will be inserted at the bottom level in such a way that it satisfies Binary Search tree property also (refer to *Figure 7.29*).



**Figure 7.29: After inserting node 50**



**Figure 7.30: Split at node 39(left rotation)**

Now, we should be aware as to how this left rotation is performed. Remember, that rotation is introduced in Red-black tree and these rotations (left and right) are the same as we performed in a Red-Black tree. Now, again `split()` has removed its condition but has created skew conditions (refer to *Figure 7.30*). So, `skew()` function will now be called again and again until a complete AA-tree with no falsecondition is obtained.

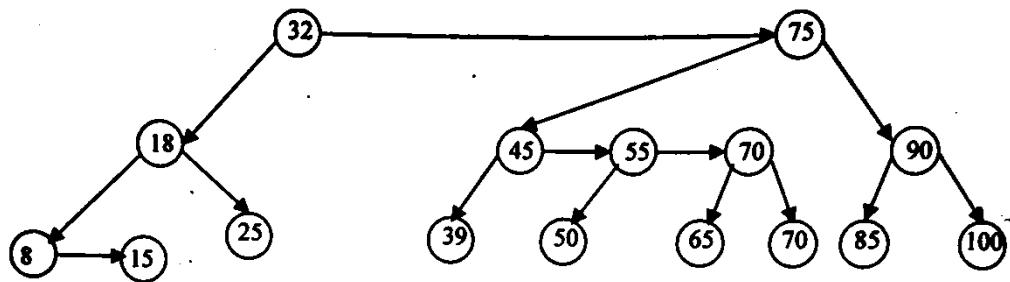


Figure 7.31: Skew at 55 (right rotation)

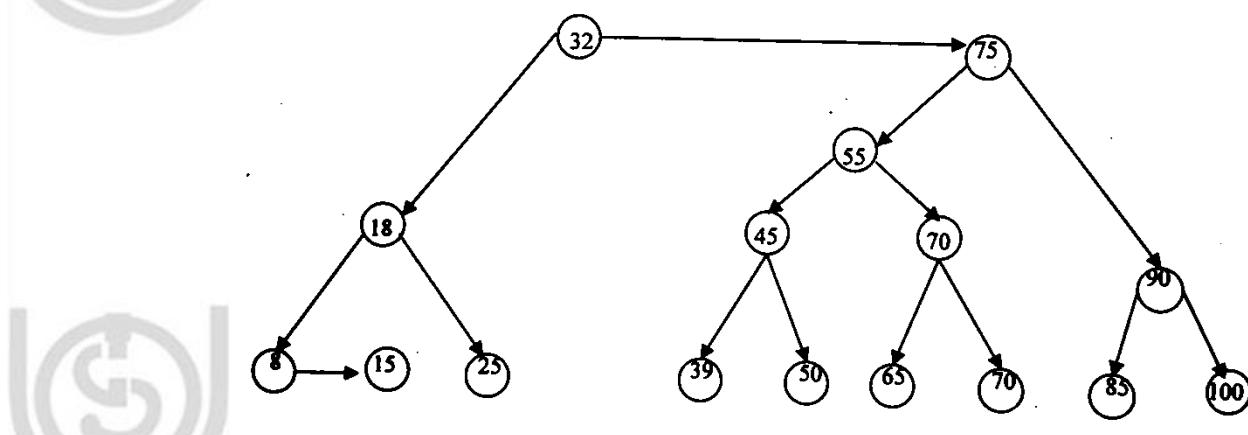


Figure 7.32: Split at 45

A skew problem arises because node 90 is two-level lower than its parent 75 and so in order to avoid this, we call skew / split function again.

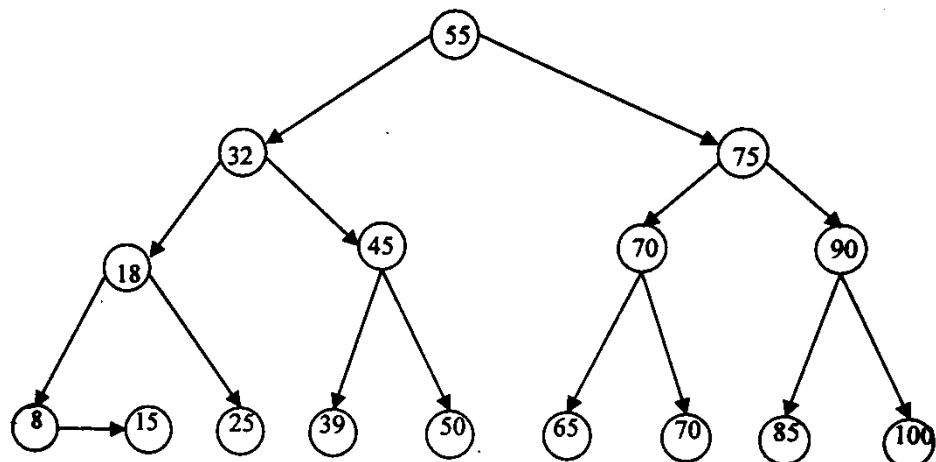


Figure 7.33 : The Final AA-tree

Thus, introducing horizontal left links, in order to avoid left horizontal links and

making them right horizontal links, we make 3 calls to skew and then 2 calls to split to remove consecutive horizontal links (refer to *Figures 7.31, 7.32 and 7.33*).

A Treap is another type of Binary Search tree and has one property different from other types of trees. Each node in the tree stores an item, a left and right pointer and a priority that is randomly assigned when the node is created. While assigning the priority, it is necessary that the heap order priority should be maintained: node's priority should be at least as large as its parent's. A treap is both binary search tree with respect to node elements and a heap with respect to node priorities.

## 7.8 SUMMARY

In this unit, we discussed Binary Search Trees, AVL trees and B-trees.

The striking feature of Binary Search Trees is that all the elements of the left subtree of the root will be less than those of the right subtree. The same rule is applicable for all the subtrees in a BST. An AVL tree is a Height balanced tree. The heights of left and right subtrees of root of an AVL tree differ by 1. The same rule is applicable for all the subtrees of the AVL tree. A B-tree is a m-ary binary tree. There can be multiple elements in each node of a B-tree. B-trees are used extensively to insert , delete and retrieve records from the databases.

## 7.9 SOLUTIONS/ANSWERS

### Check Your Progress 1

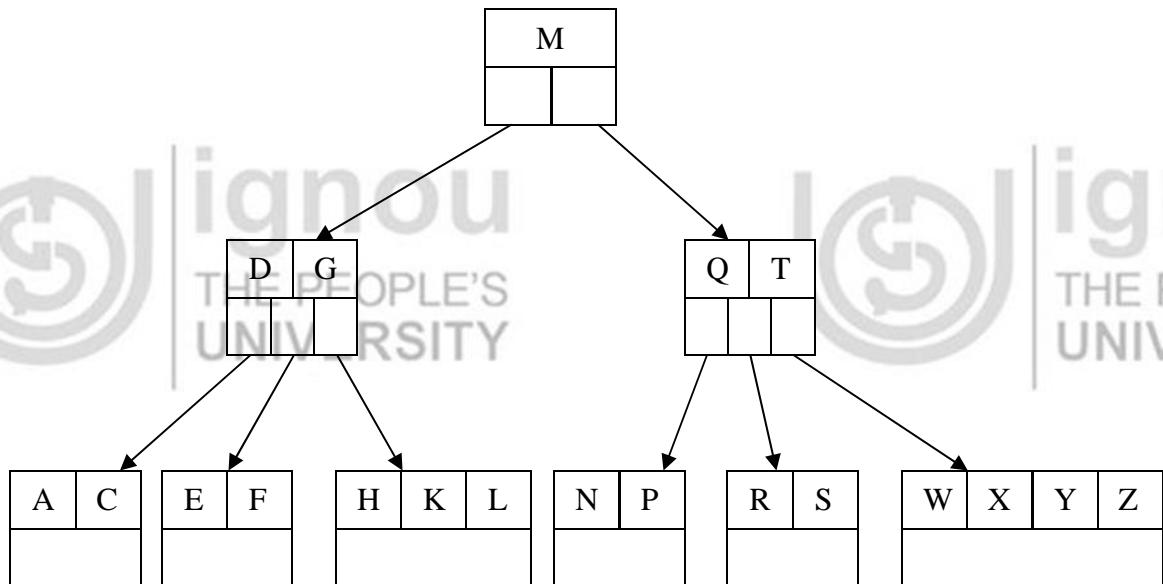
- 1) preorder, postorder and inorder
- 2) The major feature of a Binary Search Tree is that all the elements whose values is less than the root reside in the nodes of left subtree of the root and all the elements whose values are larger than the root reside in the nodes of right subtree of the root. The same rule is applicable to all the left and right subtrees of a BST.

### Check Your Progress 2

- 1) The following is the structure of an AVL tree:  

```
struct avl {
    struct node *left;
    int info;int bf;
    struct node *right;
};
```

1)



- 2) A multiway tree of order n is an ordered tree where each node has at most m children. For each node, if k is the actual no. of children in the node, then  $k-1$  is the number of keys in the node. If the keys and subtrees are arranged in the fashion of a search tree, then this is multiway search tree of order m.

## 7.10 FURTHER READINGS

1. *Data Structures using C and C ++* by Yedidyah Hangsam, Moshe J. Augenstein and Aaron M. Tanenbaum, PHI Publications.
2. *Fundamentals of Data Structures in C* by R.B. Patel, PHI Publications.

### Reference Websites

<http://www.cs.umbc.edu> <http://www.fredosaurus.com>

## UNIT 8 GRAPHS

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## 8.0 INTRODUCTION

In this unit, we will discuss a data structure called Graph. In fact, graph is a general tree with no parent-child relationship. Graphs have many applications in computer science and other fields of science. In general, graphs represent a relatively less restrictive relationship between the data items. We shall discuss about both undirected graphs and directed graphs. The unit also includes information on different algorithms which are based on graphs.

## 8.1 OBJECTIVES

After going through this unit, you should be able to

- know about graphs and related terminologies;
- know about directed and undirected graphs along with their representations;
- know different shortest path algorithms;
- construct minimum cost spanning trees;
- apply depth first search and breadth first search algorithms, and
- finding strongly connected components of a graph.

## 8.2 DEFINITIONS

A graph **G** may be defined as a finite set **V** of vertices and a set **E** of edges (pair of connected vertices). The notation used is as follows:

Graph  $G = (V, E)$

Consider the graph of *Figure 8.1*.

The set of vertices for the graph is  $V = \{1, 2, 3, 4, 5\}$ .

The set of edges for the graph is  $E = \{(1,2), (1,5), (1,3), (5,4), (4,3), (2,3)\}$ .

The elements of E are always a pair of elements.

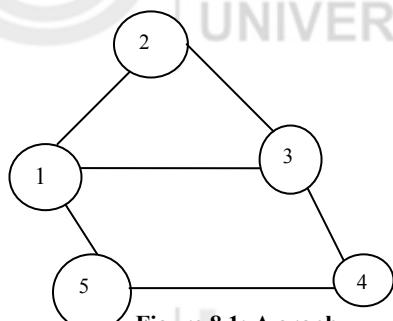


Figure 8.1: A graph

It may be noted that unlike nodes of a tree, graph has a very limited relationship between the nodes (vertices). There is no direct relationship between the vertices 1 and 4 although they are connected through 3.

**Directed graph and Undirected graph:** If every edge  $(a,b)$  in a graph is marked by a direction from a to b, then we call it a Directed graph (digraph). On the other hand, if directions are not marked on the edges, then the graph is called an Undirected graph.

In a Directed graph, the edges  $(1,5)$  and  $(5,1)$  represent two different edges whereas in an Undirected graph,  $(1,5)$  and  $(5,1)$  represent the same edge. Graphs are used in various types of modeling. For example, graphs can be used to represent connecting roads between cities.

#### Graph terminologies :

**Adjacent vertices:** Two vertices a and b are said to be adjacent if there is an edge connecting a and b. For example, in Figure 8.1, vertices 5 and 4 are adjacent.

**Path:** A path is defined as a sequence of distinct vertices, in which each vertex is adjacent to the next. For example, the path from 1 to 4 can be defined as a sequence of adjacent vertices  $(1,5), (5,4)$ .

A path,  $p$ , of length,  $k$ , through a graph is a sequence of connected vertices:

$$p = \langle v_0, v_1, \dots, v_k \rangle$$

**Cycle :** A graph contains cycles if there is a path of non-zero length through the graph,  $p = \langle v_0, v_1, \dots, v_k \rangle$  such that  $v_0 = v_k$ .

**Edge weight :** It is the cost associated with edge.

**Loop:** It is an edge of the form  $(v,v)$ .

**Path length :** It is the number of edges on the path.

**Simple path :** It is the set of all distinct vertices on a path (except possibly first and last).

**Spanning Trees:** A spanning tree of a graph, G, is a set of  $|V|-1$  edges that connect all vertices of the graph.

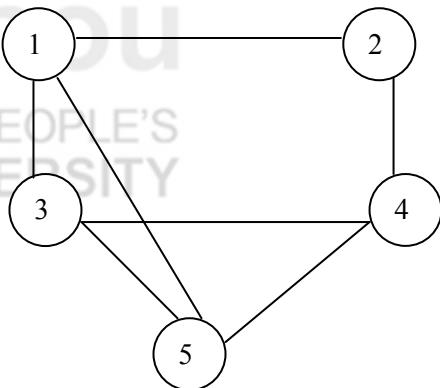
There are different representations of a graph. They are:

- Adjacency list representation
- Adjacency matrix representation

### Adjacency list representation

An Adjacency list representation of a Graph  $G = \{V, E\}$  consists of an array of adjacency lists denoted by *adj of V* list. For each vertex  $u \in V$ ,  $\text{adj}[u]$  consists of all vertices adjacent to  $u$  in the graph  $G$ .

Consider the graph of *Figure 8.2*.



**Figure 8.2: A Graph**

The following is the adjacency list representation of graph of *Figure 8.2*:

$\text{adj}[1] = \{2, 3, 5\}$   
 $\text{adj}[2] = \{1, 4\}$   
 $\text{adj}[3] = \{1, 4, 5\}$   
 $\text{adj}[4] = \{2, 3, 5\}$   
 $\text{adj}[5] = \{1, 3, 4\}$

An adjacency matrix representation of a Graph  $G = (V, E)$  is a matrix  $A(a_{ij})$  such that

$$a_{ij} = \begin{cases} 1 & \text{if edge } (i, j) \text{ belongs to } E \\ 0 & \text{otherwise} \end{cases}$$

The adjacency matrix for the graph of *Figure 8.2* is given below:

|   | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 0 | 1 | 1 | 0 | 1 |
| 2 | 1 | 0 | 0 | 1 | 1 |
| 3 | 1 | 0 | 0 | 1 | 1 |
| 4 | 0 | 1 | 1 | 0 | 1 |
| 5 | 1 | 0 | 1 | 1 | 0 |

Observe that the matrix is symmetric along the main diagonal. If we define the adjacency matrix as  $A$  and the transpose as  $A^T$ , then for an undirected graph  $G$  as above,  $A = A^T$ .

*Graph connectivity :*

A connected graph is a graph in which path exists between every pair of vertices.

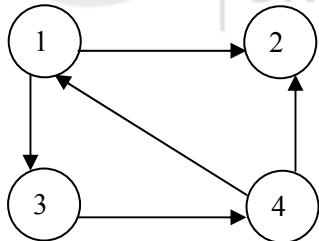
A strongly connected graph is a directed graph in which every pair of distinct vertices are connected with each other.

A weakly connected graph is a directed graph whose underlying graph is connected, but not strongly connected.

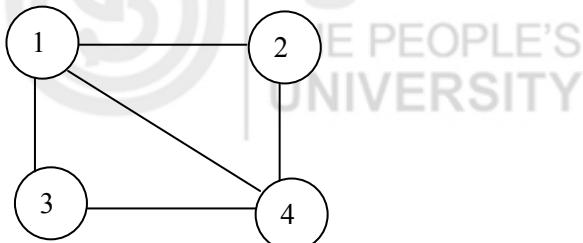
A complete graph is a graph in which there exists edge between every pair of vertices.

### ☛ Check Your Progress 1

- 1) A graph with no cycle is called \_\_\_\_\_ graph.
- 2) Adjacency matrix of an undirected graph is \_\_\_\_\_ on main diagonal.
- 3) Represent the following graphs(*Figure 8.3* and *Figure 8.4*) by adjacency matrix:



**Figure 8.3: A Directed Graph**



**Figure 8.4: A Graph**

---

## 8.3 SHORTEST PATH ALGORITHMS

---

A driver takes shortest possible route to reach destination. The problem that we will discuss here is similar to this kind of finding shortest route in a graph. The graphs are weighted directed graphs. The weight could be time, cost, losses other than distance designated by numerical values.

*Single source shortest path problem :* To find a shortest path from a single source to every vertex of the Graph.

Consider a Graph  $G = (V, E)$ . We wish to find out the shortest path from a single source vertex  $s \in V$ , to every vertex  $v \in V$ . The single source shortest path algorithm (Dijkstra's Algorithm) is based on assumption that no edges have negative weights.

The procedure followed to find shortest path are based on a concept called relaxation. This method repeatedly decreases the upper bound of actual shortest path of each vertex from the source till it equals the shortest-path weight. Please note that shortest path between two vertices contains other shortest path within it.

### 8.3.1 Dijkstra's Algorithm

Dijkstra's algorithm (named after its discover, Dutch computer scientist E.W. Dijkstra) solves the problem of finding the shortest path from a point in a graph (the *source*) to a destination with non-negative weight edge.

It turns out that one can find the shortest paths from a given source to *all* vertices (points) in a graph in the same time. Hence, this problem is sometimes called the *single-source shortest paths* problem. Dijkstra's algorithm is a greedy algorithm, which finds shortest path between all pairs of vertices in the graph. Before describing the algorithms formally, let us study the method through an example.

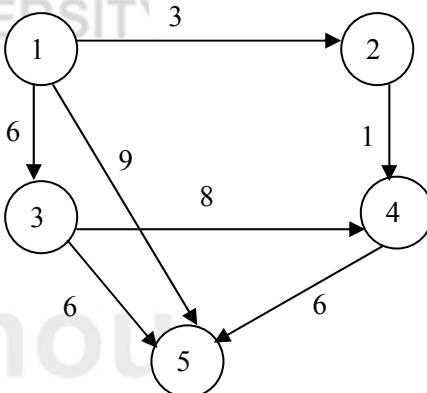


Figure 8.5: A Directed Graph with no negative edge(s)

Dijkstra's algorithm keeps two sets of vertices:

**S** is the set of vertices whose shortest paths from the source have already been determined

**Q = V-S** is the set of remaining vertices .

The other data structures needed are:

**d** array of best estimates of shortest path to each vertex from the source

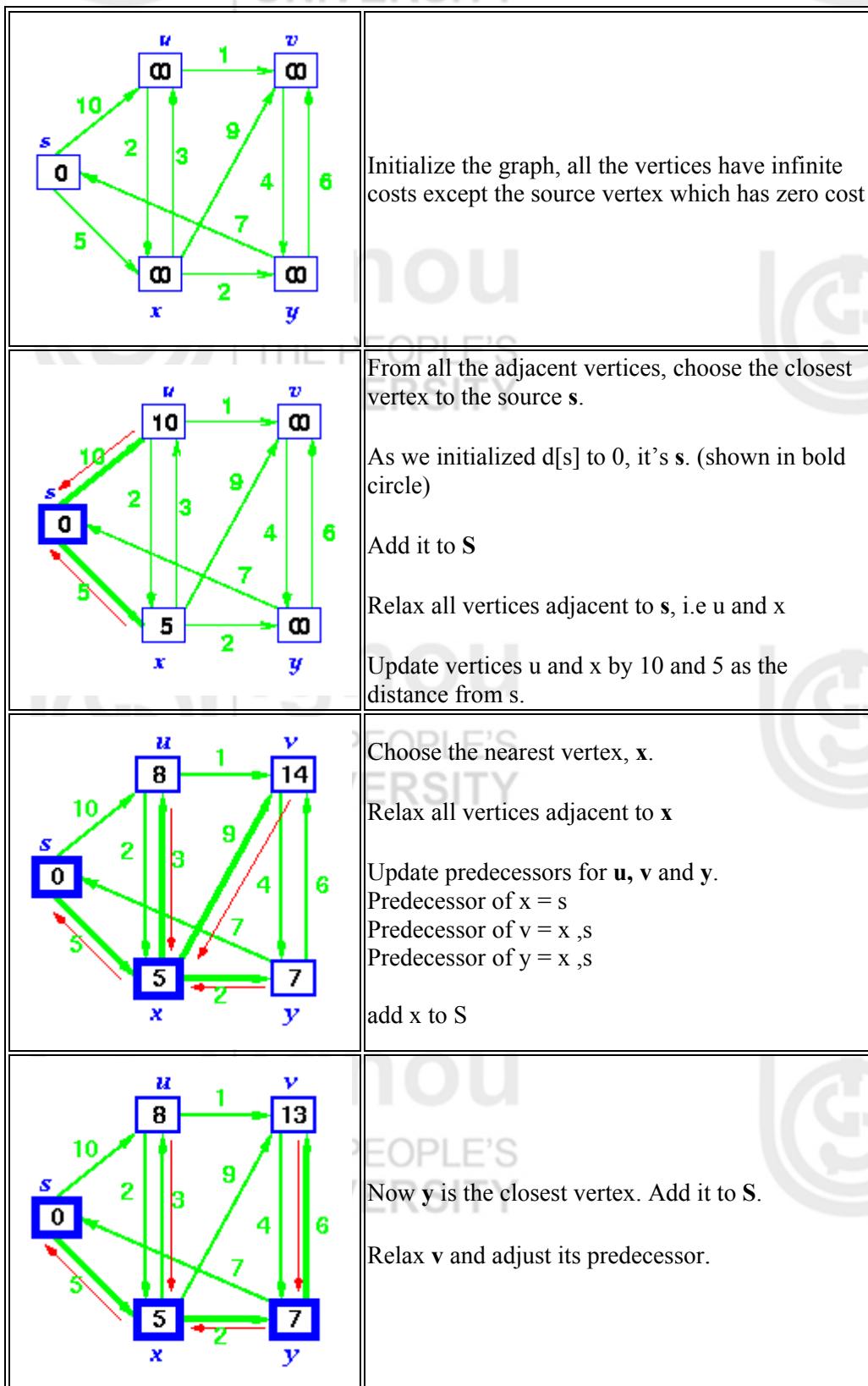
**pi** an array of predecessors for each vertex. *predecessor* is an array of vertices to which shortest path has already been determined.

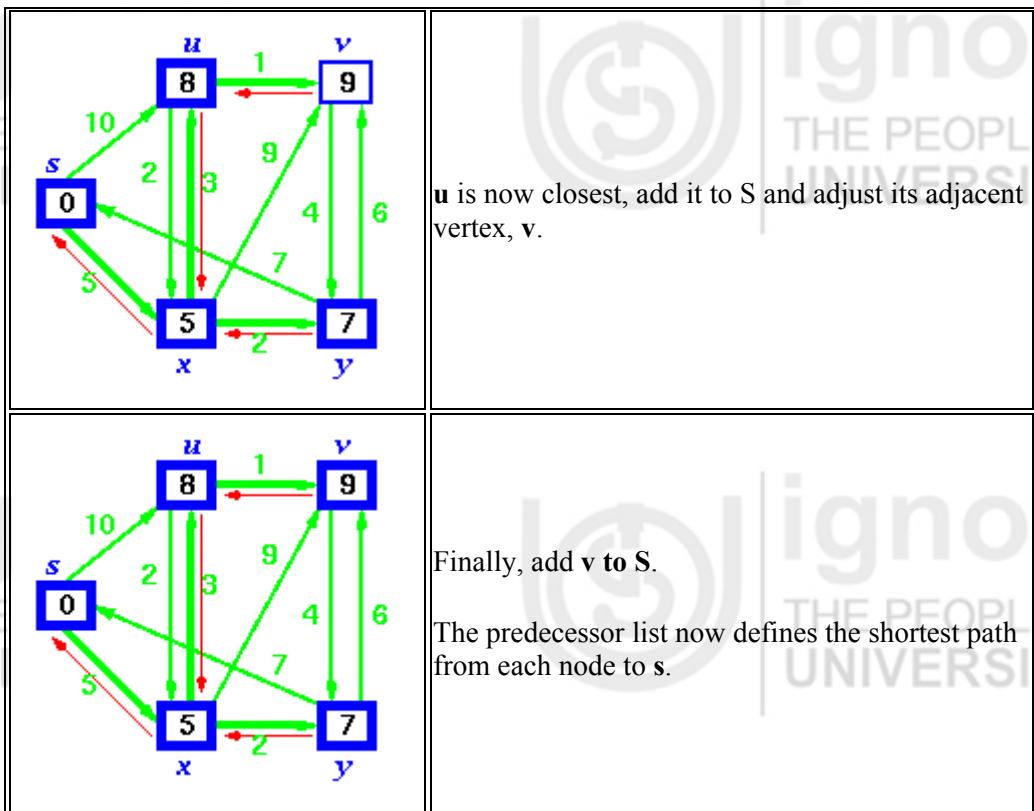
The basic operation of Dijkstra's algorithm is edge relaxation. If there is an edge from  $u$  to  $v$ , then the shortest known path from  $s$  to  $u$  can be extended to a path from  $s$  to  $v$  by adding edge  $(u,v)$  at the end. This path will have length  $d[u]+w(u,v)$ . If this is less than  $d[v]$ , we can replace the current value of  $d[v]$  with the new value.

The predecessor list is an array of indices, one for each vertex of a graph. Each vertex entry contains the index of its predecessor in a path through the graph.

## Operation of Algorithm

The following sequence of diagrams illustrate the operation of Dijkstra's Algorithm.  
The bold vertices indicate the vertex to which shortest path has been determined.





$u$  is now closest, add it to  $S$  and adjust its adjacent vertex,  $v$ .

Finally, add  $v$  to  $S$ .

The predecessor list now defines the shortest path from each node to  $s$ .

### Dijkstra's algorithm

```

* Initialise d and pi*
for each vertex  $v$  in  $V(g)$ 
     $g.d[v] := \infty$ 
     $g.pi[v] := \text{nil}$ 
     $g.d[s] := 0;$ 
* Set S to empty *
 $S := \{ 0 \}$ 
 $Q := V(g)$ 
* While ( $V-S$ ) is not null*
while not Empty( $Q$ )

```

1. Sort the vertices in  $V-S$  according to the current best estimate of their distance from the source  
 $u := \text{Extract-Min} ( Q );$
2. Add vertex  $u$ , the closest vertex in  $V-S$ , to  $S$ ,  
 $\text{AddNode}( S, u );$
3. Relax all the vertices still in  $V-S$  connected to  $u$   
 $\text{relax( Node } u, \text{ Node } v, \text{ double } w[][])$   
if  $d[v] > d[u] + w[u][v]$  then  
 $d[v] := d[u] + w[u][v]$   
 $pi[v] := u$

In summary, this algorithm starts by assigning a weight of infinity to all vertices, and then selecting a source and assigning a weight of zero to it. Vertices are added to the set for which shortest paths are known. When a vertex is selected, the weights of its adjacent vertices are relaxed. Once all vertices are relaxed, their predecessor's vertices

are updated ( $\pi_i$ ). The cycle of selection, weight relaxation and predecessor update is repeated until the shortest path to all vertices has been found.

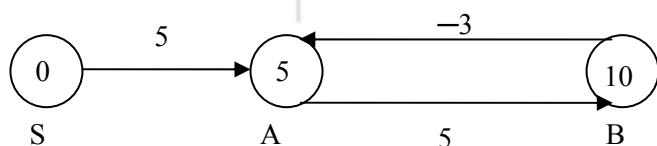
### Complexity of Algorithm

The simplest implementation of the Dijkstra's algorithm stores vertices of set  $Q$  in an ordinary linked list or array, and operation Extract-Min( $Q$ ) is simply a linear search through all vertices in  $Q$ . In this case, the running time is  $\Theta(n^2)$ .

### 8.3.2 Graphs with Negative Edge costs

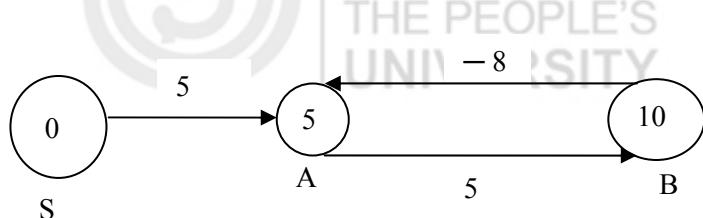
We have seen that the above Dijkstra's single source shortest-path algorithm works for graphs with non-negative edges (like road networks). The following two scenarios can emerge out of negative cost edges in a graph:

- Negative edge with non-negative weight cycle reachable from the source.
- Negative edge with non-negative weight cycle reachable from source.



**Figure 8.6 : A Graph with negative edge and non-negative weight cycle**

The net weight of the cycle is  $2(\text{non-negative})$  (refer to *Figure 8.6*).



**Figure 8.7: A graph with negative edge and negative weight cycle**

The net weight of the cycle is  $-3(\text{negative})$  (refer to *Figure 8.7*). The shortest path from A to B is not well defined as the shortest path to this vertex are infinite, i.e., by traveling each cycle we can decrease the cost of the shortest path by 3, like (S, A, B) is path (S, A, B, A, B) is a path with less cost and so on.

Dijkstra's Algorithm works only for directed graphs with non-negative weights (cost).

### 8.3.3 Acyclic Graphs

A path in a directed graph is said to form a cycle if there exists a path  $(A, B, C, \dots, P)$  such that  $A = P$ . A graph is called acyclic if there is no cycle in the graph.

### 8.3.4 All Pairs Shortest Paths Algorithm

In the last section, we discussed about shortest path algorithm which starts with a single source and finds shortest path to all vertices in the graph. In this section, we shall discuss the problem of finding shortest path between all pairs of vertices in a graph. This problem is helpful in finding distance between all pairs of cities in a road atlas. All pairs shortest paths problem is mother of all shortest paths problems.

In this algorithm, we will represent the graph by adjacency matrix.

The weight of an edge  $C_{ij}$  in an adjacency matrix representation of a directed graph is represented as follows

$$C_{ij} = \begin{cases} 0 & \text{if } i = j \\ \text{weight of the directed edge from } i \text{ to } j \text{ i.e } (i,j) & \text{if } i \neq j \text{ and } (i,j) \text{ belongs to } E \\ \infty & \text{if } i \neq j \text{ and } (i,j) \text{ does not belong to } E \end{cases}$$

Given a directed graph  $G = (V, E)$ , where each edge  $(v, w)$  has a non-negative cost  $C(v, w)$ , for all pairs of vertices  $(v, w)$  to find the lowest cost path from  $v$  to  $w$ .

The All pairs shortest paths problem can be considered as a generalisation of single-source-shortest-path problem, by using Dijkstra's algorithm by varying the source node among all the nodes in the graph. If negative edge(s) is allowed, then we can't use Dijkstra's algorithm.

In this section we shall use a recursive solution to all pair shortest paths problem known as Floyd-Warshall algorithm, which runs in  $O(n^3)$  time.

This algorithm is based on the following principle. For graph  $G$  let  $V = \{1, 2, 3, \dots, n\}$ . Let us consider a sub set of the vertices  $\{1, 2, 3, \dots, k\}$ . For any pair of vertices that belong to  $V$ , consider all paths from  $i$  to  $j$  whose intermediate vertices are from  $\{1, 2, 3, \dots, k\}$ . This algorithm will exploit the relationship between path  $p$  and shortest path from  $i$  to  $j$  whose intermediate vertices are from  $\{1, 2, 3, \dots, k-1\}$  with the following two possibilities:

1. If  $k$  is not an intermediate vertex in the path  $p$ , then all the intermediate vertices of the path  $p$  are in  $\{1, 2, 3, \dots, k-1\}$ . Thus, shortest path from  $i$  to  $j$  with intermediate vertices in  $\{1, 2, 3, \dots, k-1\}$  is also the shortest path from  $i$  to  $j$  with vertices in  $\{1, 2, 3, \dots, k\}$ .
2. If  $k$  is an intermediate vertex of the path  $p$ , we break down the path  $p$  into path  $p_1$  from vertex  $i$  to  $k$  and path  $p_2$  from vertex  $k$  to  $j$ . So, path  $p_1$  is the shortest path from  $i$  to  $k$  with intermediate vertices in  $\{1, 2, 3, \dots, k-1\}$ .

During iteration process we find the shortest path from  $i$  to  $j$  using only vertices  $\{1, 2, 3, \dots, k-1\}$  and in the next step, we find the cost of using the  $k^{\text{th}}$  vertex as an intermediate step. If this results in lower cost, then we store it.

After  $n$  iterations (all possible iterations), we find the lowest cost path from  $i$  to  $j$  using all vertices (if necessary).

Note the following:

Initialize the matrix

$C[i][j] = \infty$  if  $(i, j)$  does not belong to  $E$  for graph  $G = (V, E)$

Initially,  $D[i][j] = C[i][j]$

We also define a path matrix  $P$  where  $P[i][j]$  holds intermediate vertex  $k$  on the least cost path from  $i$  to  $j$  that leads to the shortest path from  $i$  to  $j$ .

### Algorithm (All Pairs Shortest Paths)

$N$  = number of rows of the graph

$D[i][j] = C[i][j]$

For  $k$  from 1 to  $n$

Do for  $i = 1$  to  $n$

Do for  $j = 1$  to  $n$

$D[i][j] = \min(d_{ij}^{(k-1)}, d_{ik}^{(k-1)} + d_{kj}^{(k-1)})$

Enddo

Enddo

Enddo

where  $d_{ij}^{(k-1)}$  = minimum path from  $i$  to  $j$  using  $k-1$  intermediate vertices

where  $d_{ik}^{(k-1)}$  = minimum path from  $i$  to  $k$  using  $k-1$  intermediate vertices

where  $d_{kj}^{(k-1)}$  = minimum path from  $k$  to  $j$  using  $k-1$  intermediate vertices

Program 8.1 gives the program segment for the All pairs shortest paths algorithm.

AllPairsShortestPaths(int N, Matrix C, Matrix P, Matrix D)

{

    int i, j, k

    if  $i = j$  then  $C[i][j] = 0$

    for ( $i = 0; i < N; i++$ )

    {

        for ( $j = 0; j < N; j++$ )

        {

$D[i][j] = C[i][j];$

$P[i][j] = -1;$

        }

$D[i][j] = 0;$

    }

    for ( $k=0; k < N; k++$ )

    {

        for ( $i=0; i < N; i++$ )

        {

            for ( $j=0; j < N; j++$ )

            {

                if ( $D[i][k] + D[k][j] < D[i][j]$ )

                {

$D[i][j] = D[i][k] + D[k][j];$

$P[i][j] = k;$

                }

            }

        }

    }

}

\*\*\*\*\* End \*\*\*\*\*

### Program 8.1 : Program segment for All pairs shortest paths algorithm

From the above algorithm, it is evident that it has  $O(N^3)$  time complexity.

Shortest path algorithms had numerous applications in the areas of Operations Research, Computer Science, Electrical Engineering and other related areas.

#### ☒ Check Your Progress 2

- 1) \_\_\_\_\_ is the basis of Dijkstra's algorithm
  - 2) What is the complexity of All pairs shortest paths algorithm?
- 

## 8.4 MINIMUM COST SPANNING TREES

A *spanning tree* of a graph is just a subgraph that contains all the vertices and is a tree (with no cycle). A graph may have many spanning trees.

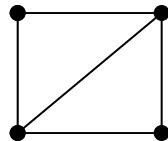


Figure 8.8: A Graph

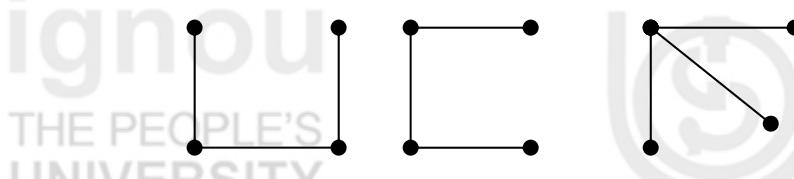


Figure 8.9 : Spanning trees of the Graph of Figure 8.9

Consider the graph of *Figure 8.8*. Its spanning trees are shown in *Figure 8.9*. Now, if the graph is a weighted graph (length associated with each edge). The weight of the tree is just the sum of weights of its edges. Obviously, different spanning trees have different weights or lengths. Our objective is to find the minimum length (weight) spanning tree.

Suppose, we have a group of islands that we wish to link with bridges so that it is possible to travel from one island to any other in the group. The set of bridges which will enable one to travel from any island to any other at minimum capital cost to the government is the minimum cost spanning tree.

#### 8.4.1 Kruskal's Algorithm

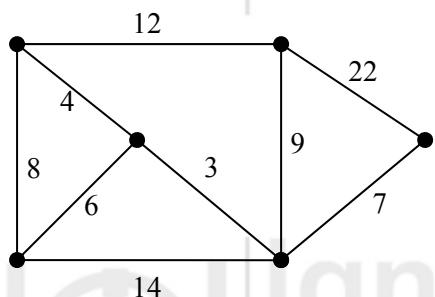
Kruskal's algorithm uses the concept of *forest* of trees. Initially the forest consists of  $n$  single node trees (and no edges). At each step, we add one (the cheapest one) edge so that it links two trees together. If it forms a cycle, it would simply mean that it links two nodes that were already connected. So, we reject it.

The steps in Kruskal's Algorithm are as follows:

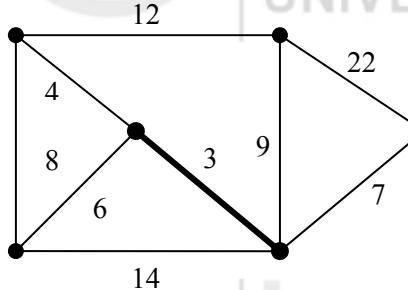
1. The forest is constructed from the graph G - with each node as a separate tree in the forest.
2. The edges are placed in a priority queue.
3. Do until we have added  $n-1$  edges to the graph,
  1. Extract the cheapest edge from the queue.
  2. If it forms a cycle, then a link already exists between the concerned nodes. Hence reject it.
  3. Else add it to the forest. Adding it to the forest will join two trees together.

The forest of trees is a partition of the original set of nodes. Initially all the trees have exactly one node in them. As the algorithm progresses, we form a union of two of the trees (sub-sets), until eventually the partition has only one sub-set containing all the nodes.

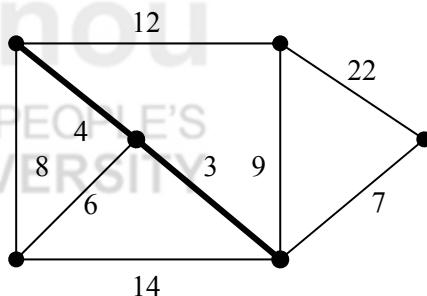
Let us see the sequence of operations to find the Minimum Cost Spanning Tree(MST) in a graph using Kruskal's algorithm. Consider the graph of *Figure 8.10.*, *Figure 8.11* shows the construction of MST of graph of *Figure 8.10.*



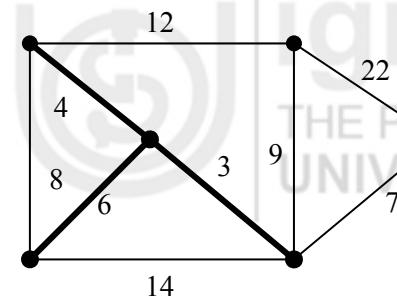
**Figure 8.10 : A Graph**



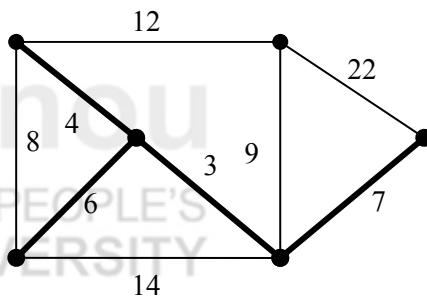
**Step 1**



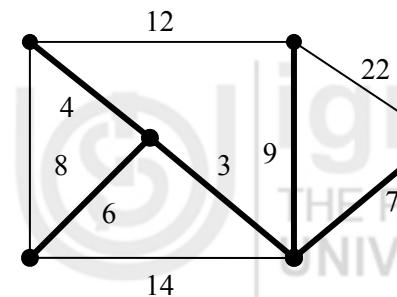
Step 2



Step 3



Step 4



Step 5

**Figure 8.11 : Construction of Minimum Cost Spanning Tree for the Graph of Figure 8.10 by application of Kruskal's algorithm**

The following are various steps in the construction of MST for the graph of *Figure 8.10* using Kruskal's algorithm.

Step 1 : The lowest cost edge is selected from the graph which is not in MST (initially MST is empty). The lowest cost edge is 3 which is added to the MST (shown in bold edges)

Step 2: The next lowest cost edge which is not in MST is added (edge with cost 4).

Step 3 : The next lowest cost edge which is not in MST is added (edge with cost 6).

Step 4 : The next lowest cost edge which is not in MST is added (edge with cost 7).

Step 5 : The next lowest cost edge which is not in MST is 8 but will form a cycle. So, it is discarded . The next lowest cost edge 9 is added. Now the MST contains all the vertices of the graph. This results in the MST of the original graph.

#### 8.4.2 Prim's Algorithm

Prim's algorithm uses the concept of sets. Instead of processing the graph by sorted order of edges, this algorithm processes the edges in the graph randomly by building up disjoint sets.

It uses two disjoint sets A and  $\bar{A}$ . Prim's algorithm works by iterating through the nodes and then finding the shortest edge from the set A to that of set  $\bar{A}$  (i.e. out side A), followed by the addition of the node to the new graph. When all the nodes are processed, we have a minimum cost spanning tree.

Rather than building a sub-graph by adding one edge at a time, Prim's algorithm builds a tree one vertex at a time.

The steps in Prim's algorithm are as follows:

Let G be the graph with n vertices for which minimum cost spanning tree is to be generated.

Let T be the minimum spanning tree.

Let T be a single vertex x.

while (T has fewer than n vertices)

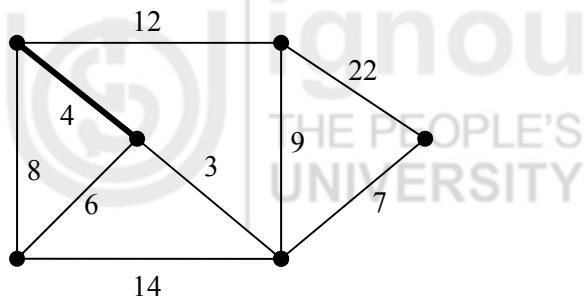
{

    find the smallest edge connecting T to G-T

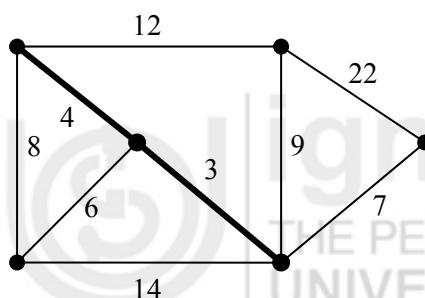
    add it to T

}

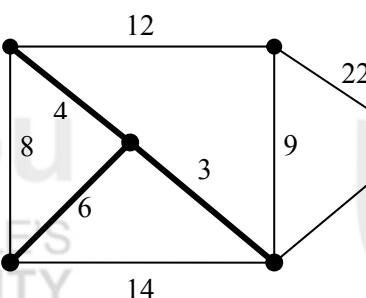
Consider the graph of *Figure 8.10*. *Figure 8.12* shows the various steps involved in the construction of Minimum Cost Spanning Tree of graph of *Figure 8.10*.



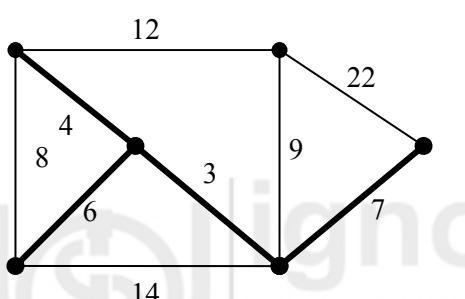
Step 1



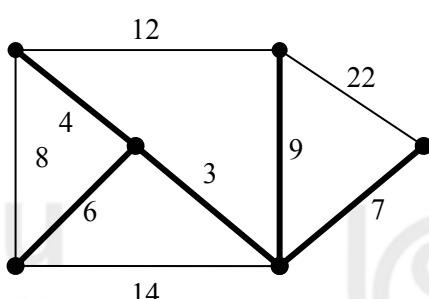
Step 2



Step 3



Step 4



Step 5

**Figure 8.12 : Construction of Minimum Cost Spanning Tree for the Graph of Figure 8.10 by application of Prim's algorithm**

The following are various steps in the construction of MST for the graph of *Figure 8.10* using Prim's algorithm.

Step 1 : We start with a single vertex (node). Now the set A contains this single node and set A' contains rest of the nodes. Add the edge with the lowest cost from A to A'. The edge with cost 4 is added.

Step 2: Lowest cost path from shaded portion of the graph to the rest of the graph (edge with cost 3) is selected and added to MST.

Step 3: Lowest cost path from shaded portion of the graph to the rest of the graph (edge with cost 6) is selected and added to MST.

Step 4: Lowest cost path from shaded portion of the graph to the rest of the graph (edge with cost 73) is selected and added to MST.

Step 5: The next lowest cost edge to the set not in MST is 8 but forms a cycle. So, it is discarded. The next lowest cost edge 9 is added. Now the MST contains all the vertices of the graph. This results in the MST of the original graph.

#### Comparison of Kruskal's algorithm and Prim's algorithm

|              | Kruskal's algorithm                                       | Prim's algorithm                                                                                                                            |
|--------------|-----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Principle    | Based on generic minimum cost spanning tree algorithms    | A special case of generic minimum cost spanning tree algorithm.<br>Operates like Dijkstra's algorithm for finding shortest path in a graph. |
| Operation    | Operates on a single set of edges in the graph            | Operates on two disjoint sets of edges in the graph                                                                                         |
| Running time | $O(E \log E)$ where E is the number of edges in the graph | $O(E \log V)$ , which is asymptotically same as Kruskal's algorithm                                                                         |

For the above comparison, it may be observed that for dense graphs having more number of edges for a given number of vertices, Prim's algorithm is more efficient.

#### 8.4.3 Applications

The minimum cost spanning tree has wide applications in different fields. It represents many complicated real world problems like:

1. Minimum distance for travelling all cities at most one (travelling salesman problem).
2. In electronic circuit design, to connect n pins by using n-1 wires, using least wire.
3. Spanning tree also finds their application in obtaining independent set of circuit equations for an electrical network.

---

## 8.5 BREADTH FIRST SEARCH (BFS)

---

When BFS is applied, the vertices of the graph are divided into two categories. The vertices, which are visited as part of the search and those vertices, which are not visited as part of the search. The strategy adopted in breadth first search is to start search at a vertex(source). Once you started at source, the number of vertices that are visited as part of the search is 1 and all the remaining vertices need to be visited. Then, search the vertices which are adjacent to the visited vertex from left to order. In this way, all the vertices of the graph are searched.

Consider the digraph of *Figure 8.13*. Suppose that the search started from S. Now, the vertices (from left to right) adjacent to S which are not visited as part of the search are B, C, A. Hence, B,C and A are visited after S as part of the BFS. Then, F is the unvisited vertex adjacent to B. Hence, the visit to B, C and A is followed by F. The unvisited vertex adjacent of C is D. So, the visit to F is followed by D. There are no

unvisited vertices adjacent to A. Finally, the unvisited vertex E adjacent to D is visited.

Hence, the sequence of vertices visited as part of BFS is S, B, C, A, F, D and E.

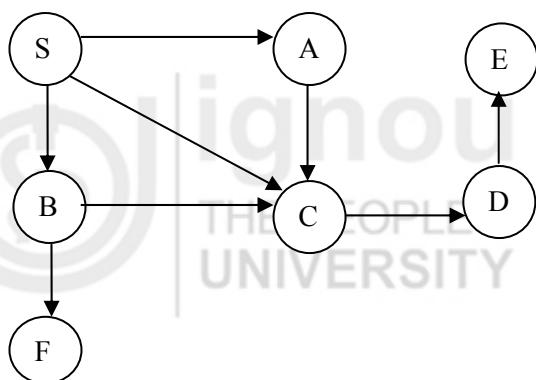
## 8.6 DEPTH FIRST SEARCH (DFS)

The strategy adopted in depth first search is to search deeper whenever possible. This algorithm repeatedly searches deeper by visiting unvisited vertices and whenever an unvisited vertex is not found, it backtracks to previous vertex to find out whether there are still unvisited vertices.

As seen, the search defined above is inherently recursive. We can find a very simple recursive procedure to visit the vertices in a depth first search. The DFS is more or less similar to pre-order tree traversal. The process can be described as below:

Start from any vertex (source) in the graph and mark it visited. Find vertex that is adjacent to the source and not previously visited using adjacency matrix and mark it visited. Repeat this process for all vertices that is not visited, if a vertex is found visited in this process, then return to the previous step and start the same procedure from there.

If returning back to source is not possible, then DFS from the originally selected source is complete and start DFS using any unvisited vertex.



**Figure 8.13 : A Digraph**

Consider the digraph of *Figure 8.13*. Start with S and mark it visited. Then visit the next vertex A, then C and then D and at last E. Now there are no adjacent vertices of E to be visited next. So, now, backtrack to previous vertex D as it also has no unvisited vertex. Now backtrack to C, then A, at last to S. Now S has an unvisited vertex B. Start DFS with B as a root node and then visit F. Now all the nodes of the graph are visited.

*Figure 8.14* shows a DFS tree with a sequence of visits. The first number indicates the time at which the vertex is visited first and the second number indicates the time at which the vertex is visited during back tracking.

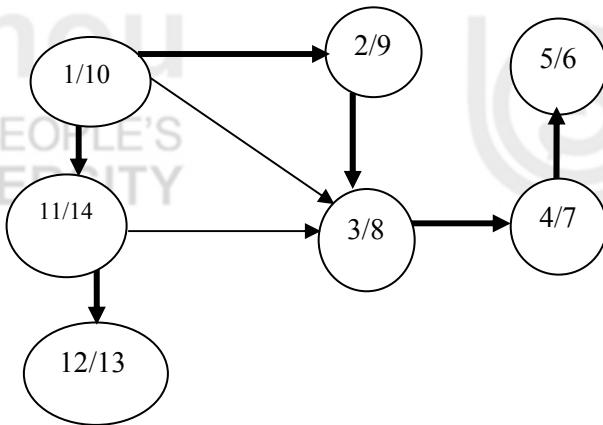


Figure 8.14 : DFS tree of digraph of Figure 8.13

The DFS forest is shown with shaded arrow in *Figure 8.14*.

#### Algorithm for DFS

Step 1: Select a vertex in the graph and make it the source vertex and mark it visited.

Step 2: Find a vertex that is adjacent to the source vertex and start a new search if it is not already visited.

Step 3: Repeat step 2 using a new source vertex. When all adjacent vertices are visited, return to previous source vertex and continue search from there.

If  $n$  is the number of vertices in the graph and the graph is represented by an adjacency matrix, then the total time taken to perform DFS is  $O(n^2)$ . If  $G$  is represented by an adjacency list and the number of edges of  $G$  are  $e$ , then the time taken to perform DFS is  $O(e)$ .

---

## 8.7 FINDING STRONGLY CONNECTED COMPONENTS

---

A beautiful application of DFS is finding a strongly connected component of a graph.

**Definition:** For graph  $G = (V, E)$ , where  $V$  is the set of vertices and  $E$  is the set of edges, we define a strongly connected components as follows:

$U$  is a sub set of  $V$  such that  $u, v$  belongs to  $U$  such that, there is a path from  $u$  to  $v$  and  $v$  to  $u$ . That is, all pairs of vertices are reachable from each other.

In this section we will use another concept called transpose of a graph. Given a directed graph  $G$  a transpose of  $G$  is defined as  $G^T$ .  $G^T$  is defined as a graph with the same number of vertices and edges with only the direction of the edges being reversed.  $G^T$  is obtained by transposing the adjacency matrix of the directed graph  $G$ .

The algorithm for finding these strongly connected components uses the transpose of  $G$ ,  $G^T$ .

$$G = (V, E), G^T = (V, E^T), \text{ where } E^T = \{ (u, v) : (v, u) \text{ belongs to } E \}$$

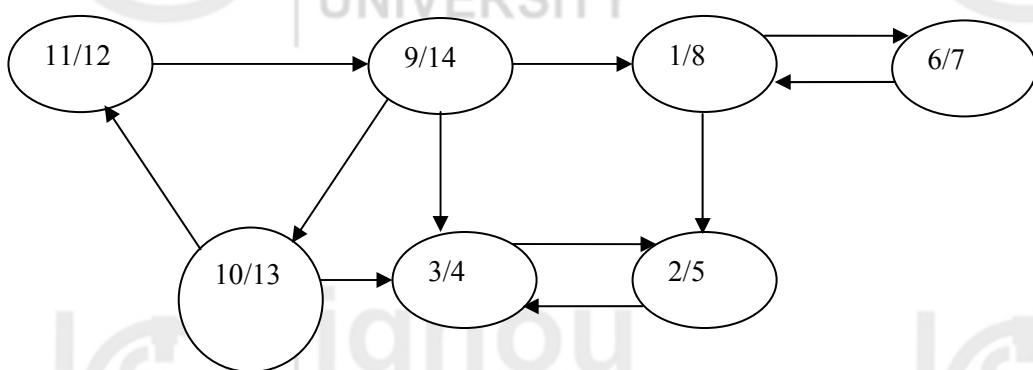


Figure 8.15: A Digraph

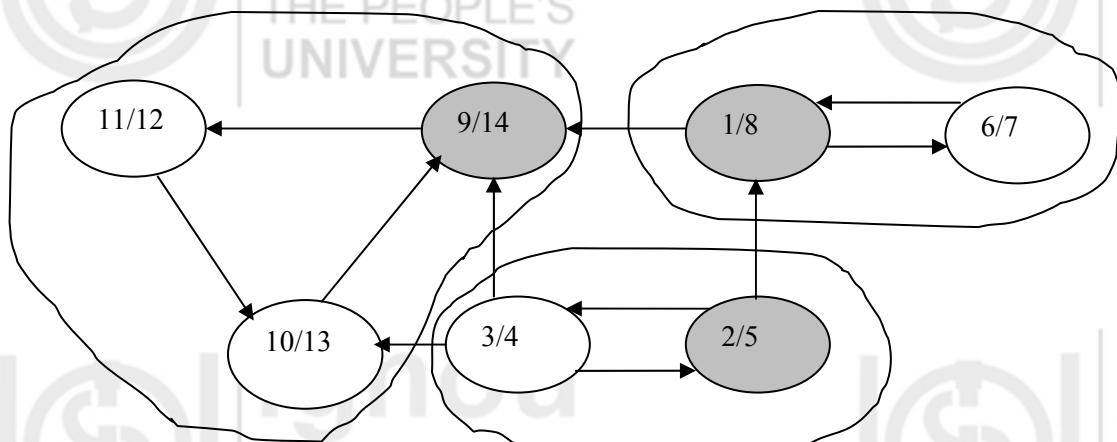


Figure 8.16: Transpose and strongly connected components of digraph of Figure 8.15

Figure 8.15 shows a directed graph with sequence in DFS (first number of the vertex shows the discovery time and second number shows the finishing time of the vertex during DFS). Figure 8.16 shows the transpose of the graph in Figure 8.15 whose edges are reversed. The strongly connected components are shown in zig-zag circle in Figure 8.16.

To find strongly connected component we start with a vertex with the highest finishing time and start DFS in the graph  $G^T$  and then in decreasing order of finishing time. DFS with vertex with finishing time 14 as root finds a strongly connected component. Similarly, vertices with finishing times 8 and then 5, when selected as source vertices also lead to strongly connected components.

#### Algorithm for finding strongly connected components of a Graph:

##### Strongly Connected Components (G)

where  $d[u]$  = discovery time of the vertex  $u$  during DFS ,  $f[u]$  = finishing time of a vertex  $u$  during DFS,  $G^T$  = Transpose of the adjacency matrix

Step 1: Use  $\text{DFS}(G)$  to compute  $f[u] \forall u \in V$

Step 2: Compute  $G^T$

Step 3: Execute  $\text{DFS}$  in  $G^T$

Step 4: Output the vertices of each tree in the depth-first forest of Step 3 as a separate strongly connected component.

### ☛ Check Your Progress 3

- 1) Which graph traversal uses a queue to hold vertices that are to be processed next?

.....  
.....

- 2) Which graph traversal is recursive by nature?

.....  
.....

- 3) For a dense graph, Prim's algorithm is faster than Kruskal's algorithm

True/False

- 4) Which graph traversal technique is used to find strongly connected component of a graph?

.....  
.....

---

## 8.8 SUMMARY

---

Graphs are data structures that consist of a set of vertices and a set of edges that connect the vertices. A graph where the edges are directed is called directed graph. Otherwise, it is called an undirected graph. Graphs are represented by adjacency lists and adjacency matrices. Graphs can be used to represent a road network where the edges are weighted as the distance between the cities. Finding the minimum distance between single source and all other vertices is called single source shortest path problem. Dijkstra's algorithm is used to find shortest path from a single source to every other vertex in a directed graph. Finding shortest path between every pair of vertices is called all pairs shortest paths problem.

A spanning tree of a graph is a tree consisting of only those edges of the graph that connects all vertices of the graph with minimum cost. Kruskal's and Prim's algorithms find minimum cost spanning tree in a graph. Visiting all nodes in a graph systematically in some manner is called traversal. Two most common methods are depth-first and breadth-first searches.

---

## 8.9 SOLUTIONS/ANSWERS

---

### Check Your Progress 1

- 1) an acyclic  
2) symmetric  
3) The adjacency matrix of the directed graph and undirected graph are as follows:

$$\begin{bmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \end{bmatrix}$$

(Refer to Figure 8.3)

$$\begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}$$

(Refer to Figure 8.3)

### Check Your Progress 2

- 1) Node relaxation
- 2)  $O(N^3)$

### Check Your Progress 3

- 1) BFS
- 2) DFS
- 3) True
- 4) DFS

## 8.10 FURTHER READINGS

1. *Fundamentals of Data Structures in C++* by E.Horowitz, Sahni and D.Mehta; Galgotia Publications.
2. *Data Structures and Program Design in C* by Kruse, C.L.Tonodo and B.Leung; Pearson Education.
3. *Data Structures and Algorithms* by Alfred V.Aho; Addison Wesley.

### Reference Websites

- <http://www.onesmartclick.com/engineering/data-structure.html>
- <http://msdn.microsoft.com/vcsharp/programming/datastructures/>
- [http://en.wikipedia.org/wiki/Graph\\_theory](http://en.wikipedia.org/wiki/Graph_theory)

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## UNIT 9      SEARCHING AND SORTING TECHNIQUES

---

### Structure

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## 9.0    INTRODUCTION

---

Searching is the process of looking for something: Finding one piece of data that has been stored within a whole group of data. It is often the most time-consuming part of many computer programs. There are a variety of methods, or algorithms, used to search for a data item, depending on how much data there is to look through, what kind of data it is, what type of structure the data is stored in, and even where the data is stored - inside computer memory or on some external medium.

Till now, we have studied a variety of data structures, their types, their use and so on. In this unit, we will concentrate on some techniques to **search** a particular data or piece of information from a large amount of data. There are basically two types of searching techniques, **Linear or Sequential Search and Binary Search**.

Searching is very common task in day-to-day life, where we are involved some or other time, in searching either for some needful at home or office or market, or searching a word in dictionary. In this unit, we see that if the things are organised in some manner, then search becomes efficient and fast.

All the above facts apply to our computer programs also. Suppose we have a telephone directory stored in the memory in an array which contains Name and Numbers. Now, what happens if we have to find a number? The answer is search that number in the array according to name (given). If the names were organised in some order, searching would have been fast.

*So, basically a search algorithm is an algorithm which accepts an argument 'a' and tries to find the corresponding data where the match of 'a' occurs in a file or in a table.*

---

## 9.1    OBJECTIVES

---

After going through this unit, you should be able to:

- know the basic concepts of searching;
- know the process of performing the Linear Search;

- know the process of performing the Binary Search and
- know the applications of searching.

## 9.2 LINEAR SEARCH

Linear search is not the most efficient way to search for an item in a collection of items. However, it is very simple to implement. Moreover, if the array elements are arranged in random order, it is the only reasonable way to search. In addition, efficiency becomes important only in large arrays; if the array is small, there aren't many elements to search and the amount of time it takes is not even noticed by the user. Thus, for many situations, linear search is a perfectly valid approach.

Before studying Linear Search, let us define some terms related to search.

A **file** is a collection of records and a record is in turn a collection of fields. A field, which is used to differentiate among various records, is known as a '**key**'.

For example, the telephone directory that we discussed in previous section can be considered as a file, where each record contains two fields: name of the person and phone number of the person.

Now, it depends on the application whose field will be the 'key'. It can be the name of person (usual case) and it can also be phone number. We will locate any particular record by matching the input argument 'a' with the key value.

The simplest of all the searching techniques is *Linear or Sequential Search*. As the name suggests, all the records in a file are searched sequentially, one by one, for the matching of key value, until a match occurs.

The Linear Search is applicable to a table which it should be organised in an array. Let us assume that a file contains 'n' records and a record has 'a' fields but only one key. The values of key are organised in an array say 'm'. As the file has 'n' records, the size of array will be 'n' and value at position R(i) will be the key of record at position i. Also, let us assume that 'el' is the value for which search has to be made or it is the search argument.

Now, let us write a simple algorithm for Linear Search.

### Algorithm

Here, m represents the unordered array of elements  
 n represents number of elements in the array and  
 el represents the value to be searched in the list

Sep 1: [Initialize]

```

k=0
flag=1
```

Step 2: Repeat step 3 for k=0,1,2.....n-1

Step 3: if (m[k]=el )

then

```

  flag=0
  print "Search is successful" and element is found at location (k+1)
  stop
endif
```

Step 4: if (flag=1) then  
    print “Search is unsuccessful”

endif

Step 5: stop

Program 9.1 gives the program for Linear Search.

```
/*Program for Linear Search*/  
/*Header Files*/  
#include<stdio.h>  
#include<conio.h>  
/*Global Variables*/  
int search;  
int flag;  
/*Function Declarations*/  
int input (int *, int, int);  
void linear_search (int *, int, int);  
void display (int *, int);  
/*Functions */  
void linear_search(int m[ ], int n, int el)  
{  
    int k;  
    flag = 1;  
    for(k=0; k<n; k++)  
    {  
        if(m[k]==el)  
        {  
            printf("\n Search is Successful\n");  
            printf("\n Element : %i Found at location : %i", element, k+1);  
            flag = 0;  
        }  
    }  
    if(flag==1)  
        printf("\n Search is unsuccessful");  
}  
void display(int m[ ], int n)  
{  
    int i;  
    for(i=0; i< 20; i++)  
    {  
        printf("%d", m[i]);  
    }  
}  
int input(int m[ ], int n, int el)  
{  
    int i;  
    n = 20;  
    el = 30;  
    printf("Number of elements in the list : %d", n);  
    for(i=0;i<20;i++)  
    {  
        m[i]=rand( )% 100;  
    }  
    printf("\n Element to be searched :%d", el);  
    search = el;  
    return n;  
}  
/* Main Function*/
```

```

void main()
{
    int n, el, m[200];
    number = input(m, n,el);
    el = search;
    printf("\n Entered list as follows: \n");
    display(m, n);
    linear_search(m, n, el);
    printf("\n In the following list\n");
    display(m, n);
}

```

### Program 9.1: Linear Search

Program 9.1 examines each of the key values in the array ‘m’, one by one and stops when a match occurs or the total array is searched.

#### Example:

A *telephone directory* with  $n = 10$  records and Name field as key. Let us assume that the names are stored in array ‘m’ i.e.  $m(0)$  to  $m(9)$  and the search has to be made for name “Radha Sharma”, i.e. element = “Radha Sharma”.

#### Telephone Directory

| Name            | Phone No. |
|-----------------|-----------|
| Nitin Kumar     | 25161234  |
| Preeti Jain     | 22752345  |
| Sandeep Singh   | 23405678  |
| Sapna Chowdhary | 22361111  |
| Hitesh Somal    | 24782202  |
| R.S.Singh       | 26254444  |
| Radha Sharma    | 26150880  |
| S.N.Singh       | 25513653  |
| Arvind Chittora | 26252794  |
| Anil Rawat      | 26257149  |

The above algorithm will search for element = “Radha Sharma” and will stop at 6th index of array and the required phone number is “26150880”, which is stored at position 7 i.e.  $6+1$ .

#### Efficiency of Linear Search

How many number of comparisons are there in this search in searching for a given element?

The number of comparisons depends upon where the record with the argument key appears in the array. If record is at the first place, number of comparisons is ‘1’, if record is at last position ‘n’ comparisons are made.

If it is equally likely for that the record can appear at any position in the array, then, a successful search will take  $(n+1)/2$  comparisons and an unsuccessful search will take ‘n’ comparisons.

In any case, the order of the above algorithm is  $O(n)$ .

### Check Your Progress 1

- 1) Linear search uses an exhaustive method of checking each element in the array against a key value. When a match is found, the search halts. Will sorting the array before using the linear search have any effect on its order of efficiency?

.....

- 2) In a best case situation, the element was found with the fewest number of comparisons. Where, in the list, would the key element be located?

.....

---

## 9.3 BINARY SEARCH

---

An unsorted array is searched by *linear search* that scans the array elements one by one until the desired element is found.

The reason for sorting an array is that we search the array “quickly”. Now, if the array is sorted, we can employ *binary search*, which brilliantly halves the size of the search space each time it examines one array element.

An array-based binary search selects the middle element in the array and compares its value to that of the key value. Because, the array is sorted, if the key value is less than the middle value then the key must be in the first half of the array. Likewise, if the value of the key item is greater than that of the middle value in the array, then it is known that the key lies in the second half of the array. In either case, we can, in effect, “throw out” one half of the search space or array with only one comparison.

Now, knowing that the key must be in one half of the array or the other, the binary search examines the mid value of the half in which the key must reside. The algorithm thus narrows the search area by half at each step until it has either found the key data or the search fails.

As the name suggests, binary means two, so it divides an array into *two* halves for searching. This search is applicable only to an *ordered table* (in either ascending or in descending order).

Let us write an algorithm for Binary Search and then we will discuss it. The array consists of elements stored in ascending order.

#### Algorithm

Step 1: Declare an array ‘k’ of size ‘n’ i.e. k(n) is an array which stores all the keys of a file containing ‘n’ records

Step 2: I $\leftarrow$  0

Step 3: low $\leftarrow$  0, high $\leftarrow$  n-1

Step 4: while (low  $\leq$  high) do

    mid = (low + high)/2

    if (key=k[mid]) then

        write “record is at position”, mid+1 //as the array

starts from the 0<sup>th</sup> position

    else

        if(key < k[mid]) then

            high = mid - 1

```

        else    low = mid + 1
        endif
    endif
endwhile

```

Step 5: Write “Sorry, key value not found”

Step 6: Stop

Program 9.2 gives the program for Binary Search.

```

/*Header Files*/
#include<stdio.h>
#include<conio.h>
/*Functions*/
void binary_search(int array[ ], int value, int size)
{
    int found=0;
    int high=size-1, low=0, mid;
    mid = (high+low)/2;
    printf("\n\n Looking for %d\n", value);
    while((!found)&&(high>=low))
    {
        printf("Low %d Mid%d High%d\n", low, mid, high);
        if(value==array[mid] )
        {printf("Key value found at position %d",mid+1);
         found=1;
        }
        else
        {if (value<array[mid])
           high = mid-1;
        else
           low = mid+1;
        mid = (high+low)/2;
        }
    }
    if (found==1
    printf("Search successful");
    else
    printf("Key value not found");
}
/*Main Function*/
void main(void)
{
    int array[100], i;
    /*Inputting Values to Array*/
    for(i=0;i<100;i++)
    { printf("Enter the name:");
      scanf("%d", array[i]);
    }
    printf("Result of search %d\n", binary_search(array,33,100));
    printf("Result of search %d\n", binary_search(array, 75,100));
    printf("Result of search %d\n", binary_search(array,1,100));
}

```

### Program 9.2 : Binary Search

### Example:

Let us consider a file of 5 records, i.e.,  $n = 5$   
And  $k$  is a sorted array of the keys of those 5 records.

| k | 0 |
|---|---|
| 1 |   |
| 2 |   |
| 3 |   |
| 4 |   |

Let key = 55, low = 0, high = 4

Iteration 1:  $\text{mid} = (0+4)/2 = 2$

$$k(\text{mid}) = k(2) = 33$$

Now key > k (mid)

$$\text{So low} = \text{mid} + 1 = 3$$

Iteration 2: low = 3, high = 4 ( $\text{low} \leq \text{high}$ )

$$\text{Mid} = 3+4 / 2 = 3.5 \sim 3 \text{ (integer value)}$$

Here key > k (mid)

$$\text{So low} = 3+1 = 4$$

Iteration 3: low = 4, high = 4 ( $\text{low} \leq \text{high}$ )

$$\text{Mid} = (4+4)/2 = 4$$

Here key = k(mid)

So, the record is at mid+1 position, i.e., 5

### Efficiency of Binary Search

Each comparison in the binary search reduces the number of possible candidates where the key value can be found by a factor of 2 as the array is divided in two halves in each iteration. Thus, the maximum number of key comparisons are approximately  $\log n$ . So, the order of binary search is  $O(\log n)$ .

### **Comparative Study of Linear and Binary Search**

Binary search is lots faster than linear search. Here are some comparisons:

#### **NUMBER OF ARRAY ELEMENTS EXAMINED**

| array size | linear search<br>(avg. case) | binary search<br>(worst case) |
|------------|------------------------------|-------------------------------|
| 8          | 4                            | 4                             |
| 128        | 64                           | 8                             |
| 256        | 128                          | 9                             |
| 1000       | 500                          | 11                            |
| 100,000    | 50,000                       | 18                            |

A **binary search** on an array is  $O(\log_2 n)$  because at each test, you can “throw out” one half of the search space or array whereas a **linear search** on an array is  $O(n)$ .

It is noteworthy that, for very small arrays a **linear search** can prove faster than a **binary search**. However, as the size of the array to be searched increases, the binary

search is the clear winner in terms of number of comparisons and therefore overall speed.

Still, the binary search has some drawbacks. First, it requires that the data to be searched be in sorted order. If there is even one element out of order in the data being searched, it can throw off the entire process. When presented with a set of unsorted data, the efficient programmer must decide whether to sort the data and apply a binary search or simply apply the less-efficient linear search. Is the cost of sorting the data is worth the increase in search speed gained with the binary search? If you are searching only once, then it is probably better to do a linear search in most cases.

### ☛ Check Your Progress 2

- 1) State True or False
  - a. The order of linear search in worst case is  $O(n/2)$  True/False
  - b. Linear search is more efficient than Binary search. True/False
  - c. For Binary search, the array has to be sorted in ascending order only. True/False
- 2) Write the Binary search algorithm where the array is sorted in descending order.  
.....  
.....

---

## 9.4 APPLICATIONS

---

The searching techniques are applicable to a number of places in today's world, may it be Internet, search engines, on line enquiry, text pattern matching, finding a record from database, etc.

The most important application of searching is to track a particular record from a large file, efficiently and faster.

Let us discuss some of the *applications of Searching* in the world of computers.

### 1. Spell Checker

This application is generally used in **Word Processors**. It is based on a program for checking spelling, which it checks and searches sequentially. That is, it uses the concept of *Linear Search*. The program looks up a word in a list of words from a dictionary. Any word that is found in the list is assumed to be spelled correctly. Any word that isn't found is assumed to be spelled wrong.

### 2. Search Engines

Search engines use software robots to survey the Web and build their databases. Web documents are retrieved and indexed using keywords. When you enter a query at a search engine website, your input is checked against the search engine's keyword indices. The best matches are then returned to you as hits. For checking, it uses any of the Search algorithms.

Search Engines use software programs known as robots, spiders or crawlers. A robot is a piece of software that automatically follows hyperlinks from one document to the next around the Web. When a robot discovers a new site, it sends information back to its main site to be indexed. Because Web documents are one of the least static forms of publishing (i.e., they change a lot), robots also update previously catalogued sites. How quickly and comprehensively they carry out these tasks vary from one search engine to the next.

### 3. String Pattern matching

Document processing is rapidly becoming one of the dominant functions of computers. Computers are used to edit, search and transport documents over the Internet, and to display documents on printers and computer screens. Web ‘surfing’ and Web searching are becoming significant and important computer applications, and many of the key computations in all of this document processing involves character strings and string pattern matching. For example, the Internet document formats HTML and XML are primarily text formats, with added tags for multimedia content. Making sense of the many terabytes of information on the Internet requires a considerable amount of text processing. This is accomplished using *trie* data structure, which is a tree-based structure that allows for faster searching in a collection of strings.

## 9.5 INTERNAL SORTING

In internal sorting, all the data to be sorted is available in the high speed main memory of the computer. We will study the following methods of internal sorting:

1. Insertion sort
2. Bubble sort
3. Quick sort
4. Two-way Merge sort
5. Heap sort

### 9.5.1 Insertion Sort

This is a naturally occurring sorting method exemplified by a card player arranging the cards dealt to him. He picks up the cards as they are dealt and inserts them into the required position. Thus at every step, we insert an item into its proper place in an already ordered list.

We will illustrate insertion sort with an example (refer to *Figure 9.1*) before presenting the formal algorithm.

**Example :** Sort the following list using the insertion sort method:

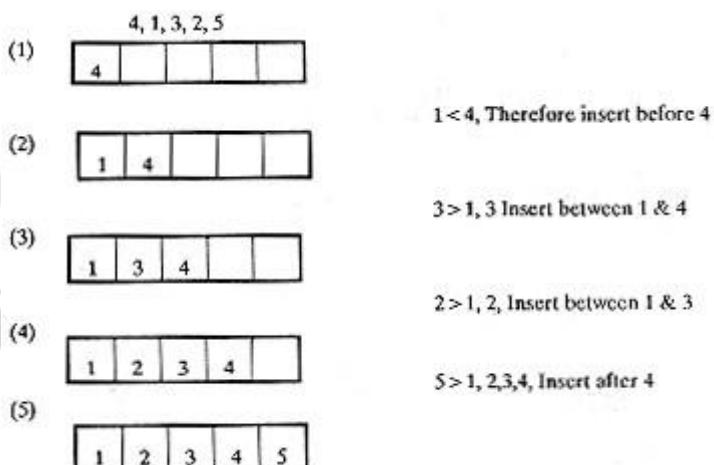


Figure 9.1 : Insertion sort

Thus to find the correct position search the list till an item just greater than the target is found. Shift all the items from this point one down the list. Insert the target in the vacated slot. Repeat this process for all the elements in the list. This results in sorted list.

### 9.5.2 Bubble Sort

In this sorting algorithm, multiple swappings take place in one pass. Smaller elements move or ‘bubble’ up to the top of the list, hence the name given to the algorithm.

In this method, adjacent members of the list to be sorted are compared. If the item on top is greater than the item immediately below it, then they are swapped. This process is carried on till the list is sorted.

The detailed algorithm follows:

#### Algorithm: BUBBLE SORT

1. Begin
2.     Read the n elements
3.         for i=1 to n
- for j=n downto i+1
- if a[j] <= a[j-1]
- swap(a[j],a[j-1])
4.         End // of Bubble Sort

Total number of comparisons in Bubble sort :

$$= (N-1) + (N-2) \dots + 2 + 1$$

$$= (N-1)*N / 2 = O(N^2)$$

This inefficiency is due to the fact that an item moves only to the next position in each pass.

### 9.5.3 Quick Sort

This is the most widely used internal sorting algorithm. In its basic form, it was invented by C.A.R. Hoare in 1960. Its popularity lies in the ease of implementation, moderate use of resources and acceptable behaviour for a variety of sorting cases. The basis of quick sort is the *divide and conquer* strategy i.e. Divide the problem [list to be sorted] into sub-problems [sub-lists], until solved sub problems [sorted sub-lists] are found. This is implemented as follows:

Choose one item A[I] from the list A[ ].

Rearrange the list so that this item is in the proper position, i.e., all preceding items have a lesser value and all succeeding items have a greater value than this item.

1. Place A[0], A[1] .. A[I-1] in sublist 1
2. A[I]
3. Place A[I + 1], A[I + 2] ... A[N] in sublist 2

Repeat steps 1 & 2 for sublist1 & sublist2 till A[ ] is a sorted list. As can be seen, this

algorithm has a recursive structure.

The *divide*' procedure is of utmost importance in this algorithm. This is usually implemented as follows:

1. Choose A[I] as the dividing element.
2. From the left end of the list (A[0] onwards) scan till an item A[R] is found whose value is greater than A[I].

3. From the right end of list [A[N] backwards] scan till an item A[L] is found whose value is less than A[1].

4. Swap A[R] & A[L].

5. Continue steps 2, 3 & 4 till the scan pointers cross. Stop at this stage.

6. At this point, sublist1 & sublist are ready.

7. Now do the same for each of sublist1 & sublist2.

Program 9.3 gives the program segment for Quick sort. It uses recursion.

```
Quicksort(A,m,n)int
A[ ],m,n
{
    int i, j, k;if
    m<n
    {
        i=m;
        j=n+1;
        k=A[m];
        do
            do
                ++i;
                while (A[i] < k);
            do
                --j;
                while (A[j] > k);
                if (i < j)
                {
                    temp = A[i];
                    A[i] = A[j];
                    A[j] = temp;
                }
                while (i < j);
        temp = A[m];
        A[m] = A[j];
        A[j] = temp;
        Quicksort(A,m,j-1);
        Quicksort(A,j+1,n);
    }
}
```

### Program 9.3 : Quick Sort

The Quick sort algorithm uses the  $O(N \log_2 N)$  comparisons on average. The performance can be improved by keeping in mind the following points.

1. Switch to a faster sorting scheme like insertion sort when the sublist size becomes comparatively small.
2. Use a better dividing element in the implementations.

It is also possible to write the non-recursive Quick sort algorithm.

### 9.5.4 2-Way Merge Sort

Merge sort is also one of the ‘divide and conquer’ class of algorithms. The basic idea in this is to divide the list into a number of sublists, sort each of these sublists and merge them to get a single sorted list. The illustrative implementation of 2 way mergesort sees the input initially as  $n$  lists of size 1. These are merged to get  $n/2$  lists of size 2. These  $n/2$  lists are merged pair wise and so on till a single list is obtained. This can be better understood by the following example. This is also called *Concatenate sort*. Figure 9.2 depicts 2-way merge sort.

Mergesort is the best method for sorting linked lists in random order. The total computing time is of the  $O(n \log_2 n)$ .

The disadvantage of using mergesort is that it requires two arrays of the same size and space for the merge phase. That is, to sort a list of size  $n$ , it needs space for  $2n$  elements.

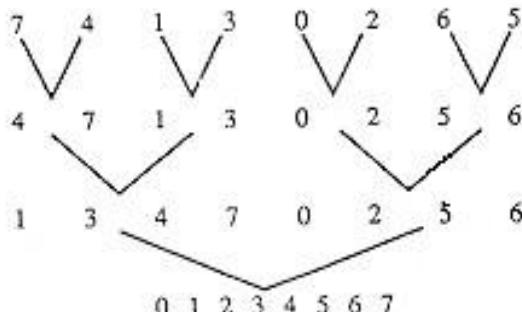


Figure 9.2: 2-way merge sort

Mergesort is the best method for sorting linked lists in random order. The total computing time is of the  $O(n \log_2 n)$ .

The disadvantage of using mergesort is that it requires two arrays of the same size and space for the merge phase. That is, to sort a list of size  $n$ , it needs space for  $2n$  elements.

### 9.5.5 Heap Sort

We will begin by defining a new structure called *Heap*. Figure 9.3 illustrates a binary tree.

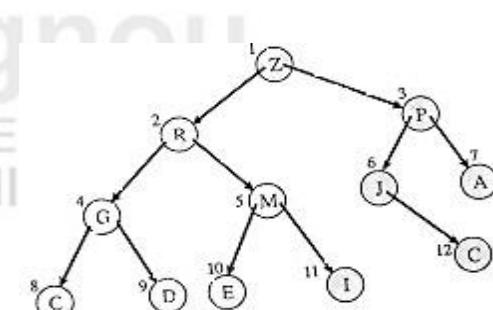


Figure 9.3: A Binary Tree

A complete binary tree is said to satisfy the ‘heap condition’ if the key of each node is greater than or equal to the key in its children. Thus the root node will have the largest key value.

Trees can be represented as arrays, by first numbering the nodes (starting from the root) from left to right. The key values of the nodes are then assigned to array positions whose index is given by the number of the node. For the example tree, the corresponding array is depicted in *Figure 9.4*.

| Index        | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|--------------|---|---|---|---|---|---|---|---|---|----|----|----|
| Array[Index] | Z | R | P | G | M | J | A | C | D | E  | I  | C  |

**Figure 9.4:** Array for the binary tree of figure 10.3

The relationships of a node can also be determined from this array representation. If a node is at position  $j$ , its children will be at positions  $2j$  and  $2j + 1$ . Its parent will be at position  $\lfloor j/2 \rfloor$ .

Consider the node M. It is at position 5. Its parent node is, therefore, at position  $5/2 = 2$  i.e. the parent is R. Its children are at positions  $2 \times 5$  &  $(2 \times 5) + 1$ , i.e. 10 + 11 respectively i.e. E & I are its children.

A *Heap* is a complete binary tree, in which each node satisfies the heap condition, represented as an array.

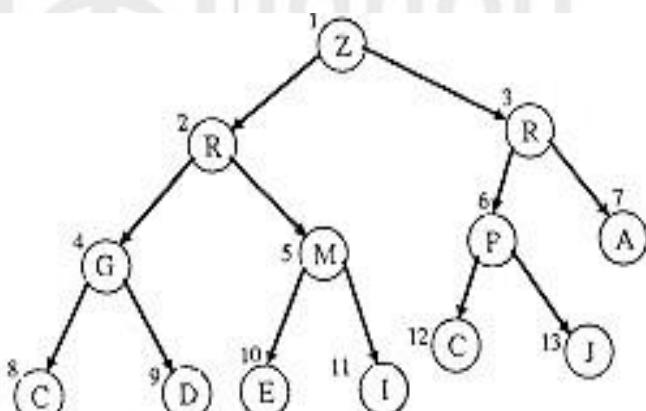
We will now study the operations possible on a heap and see how these can be combined to generate a sorting algorithm.

The operations on a heap work in 2 steps.

5. The required node is inserted/deleted/or replaced.
6. The above operation may cause violation of the heap condition so the heap is traversed and modified to rectify any such violations.

**Examples:** Consider the insertion of a node R in the heap 1.

1. Initially R is added as the right child of J and given the number 13.
2. But,  $R > J$ . So, the heap condition is violated.
3. Move R upto position 6 and move J down to position 13.
4.  $R > P$ . Therefore, the heap condition is still violated.
5. Swap R and P.
4. The heap condition is now satisfied by all nodes to get the heap of *Figure 9.5*.



**Figure 9.5:** A Heap

This algorithm is guaranteed to sort n elements in  $(n \log_2 n)$  time.

We will first see two methods of heap construction and then removal in order from the heap to sort the list.

### 1. Top down heap construction

- Insert items into an initially empty heap, satisfying the heap condition at all steps.

### 2. Bottom up heap construction

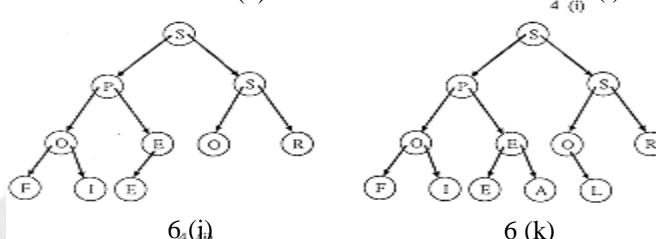
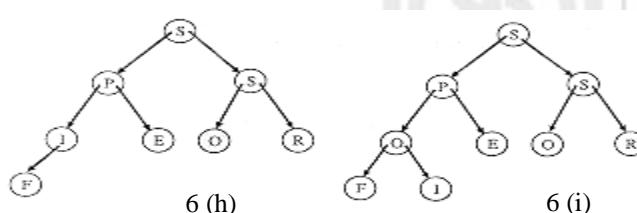
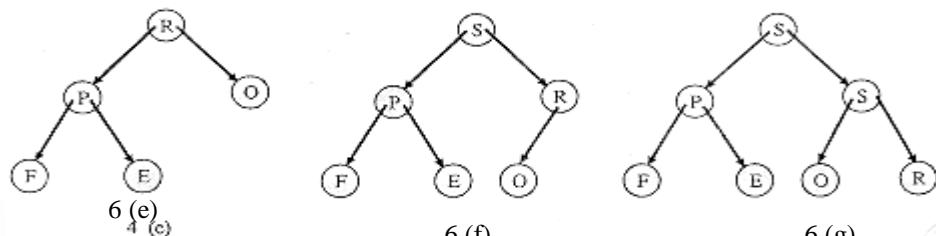
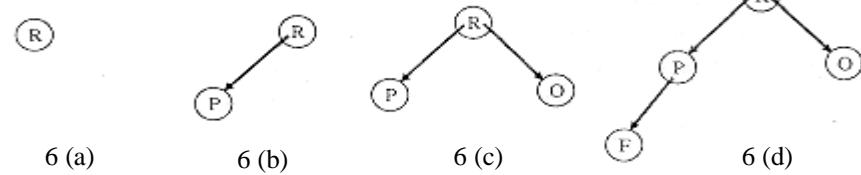
- Build a heap with the items in the order presented.
- From the right most node modify to satisfy the heap condition.

We will exemplify this with an example.

**Example:** Build a heap of the following using top down approach for heap construction.

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Figure 9.6 shows different steps of the top down construction of the heap.



**Example:** The input file is (2,3,81,64,4,25,36,16,9, 49). When the file is interpreted as a binary tree, it results in *Figure 9.7*. *Figure 9.8* depicts the heap.

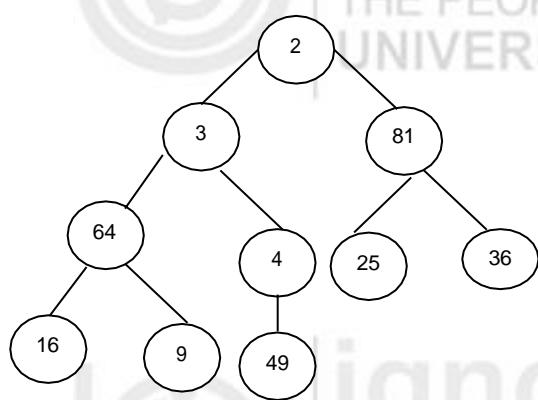


Figure 9.7: A Binary tree  
9.7

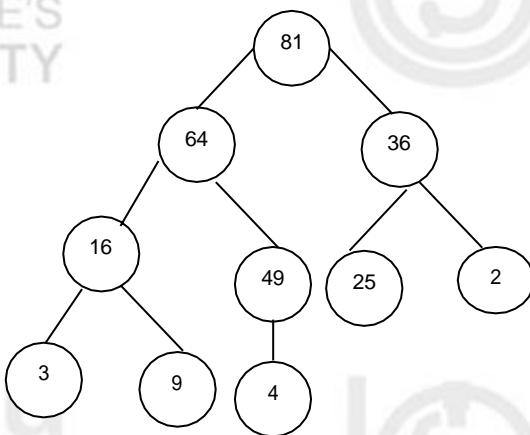
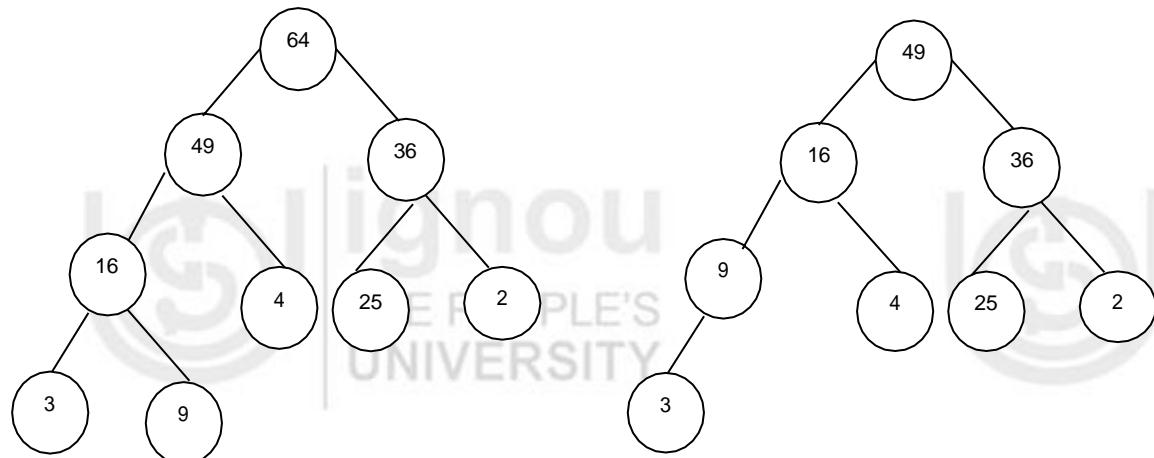


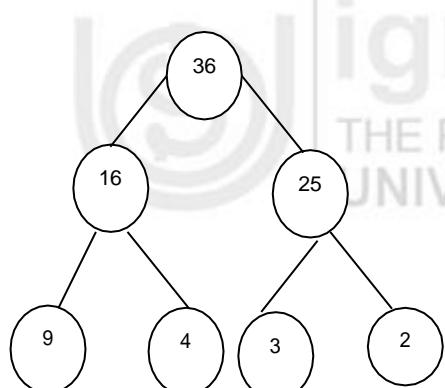
Figure 9.8: Heap of figure

Figure 9.9 illustrates various steps of the heap of *Figure 9.8* as the sorting takes place.

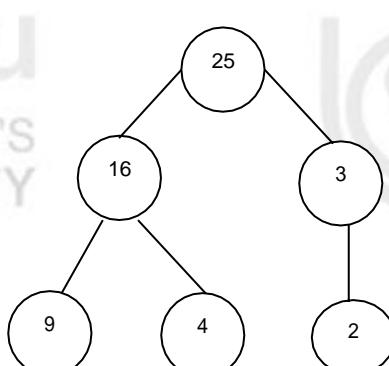


Sorted: 81  
Heap size: 9

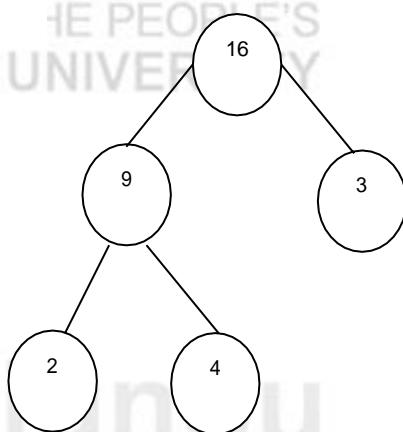
Sorted: 81,64  
Heap size: 8



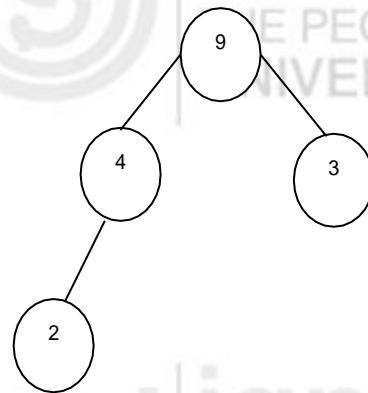
Sorted: 81,64,49  
Heap size:7



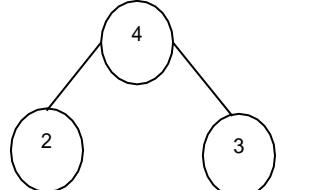
Sorted: 81,64,49,36  
Heap size:6



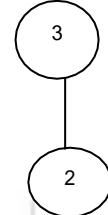
Sorted: 81, 64, 49, 36, 25  
Size: 5



Sorted: 81, 64, 49, 36, 25, 16  
Size: 4



Sorted: 81, 64, 49, 36, 25, 16, 9  
Size: 3



Sorted: 81, 64, 49, 36, 25, 16, 9, 4  
Size: 2

Sorted: 81, 64, 49, 36, 25, 16, 9, 4, 3  
Size : 1

Sorted: 81, 64, 49, 36, 25, 16, 9, 4, 3, 2  
Result

Figure 9.9 : Various steps of figure 10.8 for a sorted file

## 9.6 SORTING ON SEVERAL KEYS

So far, we have been considering sorting based on single keys. But, in real life applications, we may want to sort the data on several keys. The simplest example is that of sorting a deck of cards. The first key for sorting is the suit-clubs, spades, diamonds and hearts. Then, within each suit, sorting the cards in ascending order from Ace, twos to king. This is thus a case of sorting on 2 keys.

Now, this can be done in 2 ways.

- Sort the 52 cards into 4 piles according to the suit.
- Sort each of the 4 piles according to face value of the cards.
- Sort the 52 cards into 13 piles according to face value.
- Stack these piles in order and then sort into 4 piles based on suit.

The first method is called the MSD (Most Significant Digit) sort and the second method is called the LSD (Least Significant Digit) sort. Digit stands for a key. Though they are called sorting methods, MSD and LSD sorts only decide the *order* of sorting. The actual sorting could be done by any of the sorting methods discussed in this unit.

**Check Your Progress 3**

- 1) The complexity of Bubble sort is \_\_\_\_\_
  - 2) Quick sort algorithm uses the programming technique of \_\_\_\_\_
  - 3) Write a program in ‘C’ language for 2-way merge sort.
  - 4) The complexity of Heap sort is \_\_\_\_\_
- 

**9.7 SUMMARY**

Searching is the process of looking for something. Searching a list consisting of 100000 elements is not the same as searching a list consisting of 10 elements. We discussed two searching techniques in this unit namely Linear Search and Binary Search. Linear Search will directly search for the key value in the given list. Binary search will directly search for the key value in the given sorted list. So, the major difference is the way the given list is presented. Binary search is efficient in most of the cases. Though, it had the overhead that the list should be sorted before search can start, it is very well compensated through the time (which is very less when compared to linear search) it takes to search. There are a large number of applications of Searching out of whom a few were discussed in this unit.

**9.8 SOLUTIONS / ANSWERS****Check Your Progress 1**

- 1) No
- 2) It will be located at the beginning of the list

**Check Your Progress 2**

- 1)
- (a) F
- (b) F
- (c) F

**Check Your Progress 3**

- 1)  $O(N^2)$  where N is the number of elements in the list to be sorted.
  - 2) Divide and Conquer.
  - 3)  $O(N \log N)$  where N is the number of elements to be sorted.
- 

**9.9 FURTHER READINGS****Reference Books**

1. *Fundamentals of Data Structures in C++* by E. Horowitz, Sahai and D. Mehta, Galgotia Publications.
2. *Data Structures using C and C ++* by Yedidyah Hangsam, Moshe J. Augenstein and Aaron M. Tanenbaum, PHI Publications.
3. *Fundamentals of Data Structures in C* by R.B. Patel, PHI Publications.

**Reference Websites**

<http://www.cs.umbc.edu>    <http://www.fredosaurus.com>

# UNIT 10 HASHING

## Structure

|        |                                            |
|--------|--------------------------------------------|
| 10.0   | Introduction                               |
| 10.1   | Objectives                                 |
| 10.2   | Drivers and motivations for hashing        |
| 10.3   | Index Mapping                              |
| 10.3.1 | Challenges with Index Mapping              |
| 10.3.2 | Hash Function                              |
| 10.3.3 | Simple Hash Example                        |
| 10.4   | Collision Resolution                       |
| 10.4.1 | Separate Chaining                          |
| 10.4.2 | Open Addressing                            |
| 10.4.3 | Double Hashing                             |
| 10.5   | Comparison of Collision Resolution Methods |
| 10.6   | Load Factor and Rehashing                  |
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## 10.0 INTRODUCTION

Hashing is a key technique in information retrieval. Hashing transforms the input data into a small set of keys that can be efficiently stored and retrieved. Hashing provides constant time and highly efficient information retrieval capability irrespective of total search space.

## 10.1 OBJECTIVES

After going through this unit, you should be able to

- the drivers and motivations for hashing,
- various hashing techniques,
- understand index mapping
- collision avoiding techniques,
- understand load factor and rehashing

## 10.2 MAIN DRIVERS AND MOTIVATIONS FOR HASHING

As part of searching and information retrieval we use hashing for mainly below given reasons:

- Provide constant time data retrieval and insertion
- Manage the data related to large set of input keys efficiently
- Provide cost efficient hash key computations

## 10.3 INDEX MAPPING

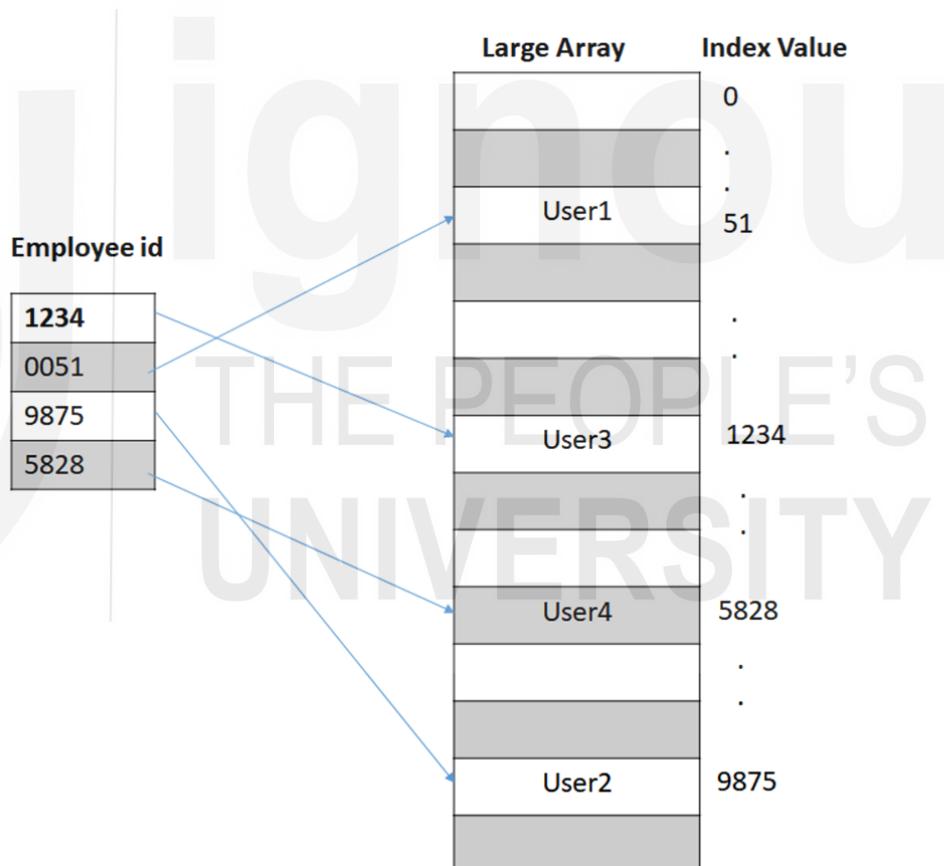
## Hashing

In order to store and retrieve huge set of data, we can think of using a large sized array and store/retrieve the data from the large array. We can plan to use the data value as the key for the array. As the array indexing takes only  $O(1)$  time, the method guarantees a constant and fast performance.

Index mapping or trivial hashing method assumes a large sized array and the input keys as index for the array to retrieve the value.

Let's look at an example for this index mapping method. Let's design a large array based on the index mapping method. We use the array to store the name of the user and we plan to lookup the user details using their 4-digit employee id. As depicted in Figure 1, we create a large array to accommodate all the employee ids and use the employee id as an index to get the user details from the array.

Index mapping approach can be used when we know or when we can predict all the input keys. For instance, if we were to store the details for months of a year we know that we can have maximum of 12 months and hence we can design the hash table with size 12. Similarly, for input keys such as days of month, countries, states within a country where we can predict the maximum values, we can use the index mapping method.



**Figure 1 Index mapping approach**

### 10.3.1 Challenges with Index Mapping

We can observe two main drawbacks with the index mapping approach. Firstly, this approach needs only non-negative integer values as the index keys and secondly as we can see from Figure 1, the array size poses performance and scalability challenges. The array has to be sized to accommodate the largest key value and the values are unevenly distributed leading to wastage of space.

To overcome the two limitations mentioned above, we need a conversion function that converts all data types (string, image, alphanumeric etc.) into a non-negative integer

value. Additionally, the conversion function also maps the input values to smaller set of keys that can be used as index for a smaller sized array. We call the conversion function as “hash function”.

Let's use a hash function that takes the input values (employee id) and converts the value into a key that forms of the index for the hash table storing the employee details. We have used the below given hash function:

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

where  $h(x)$  is the hash value,  $x$  is the input key. The mod operation provides the remainder value for the key. As a result of this hash function we now have the hash table with optimal size as depicted in Figure 2.

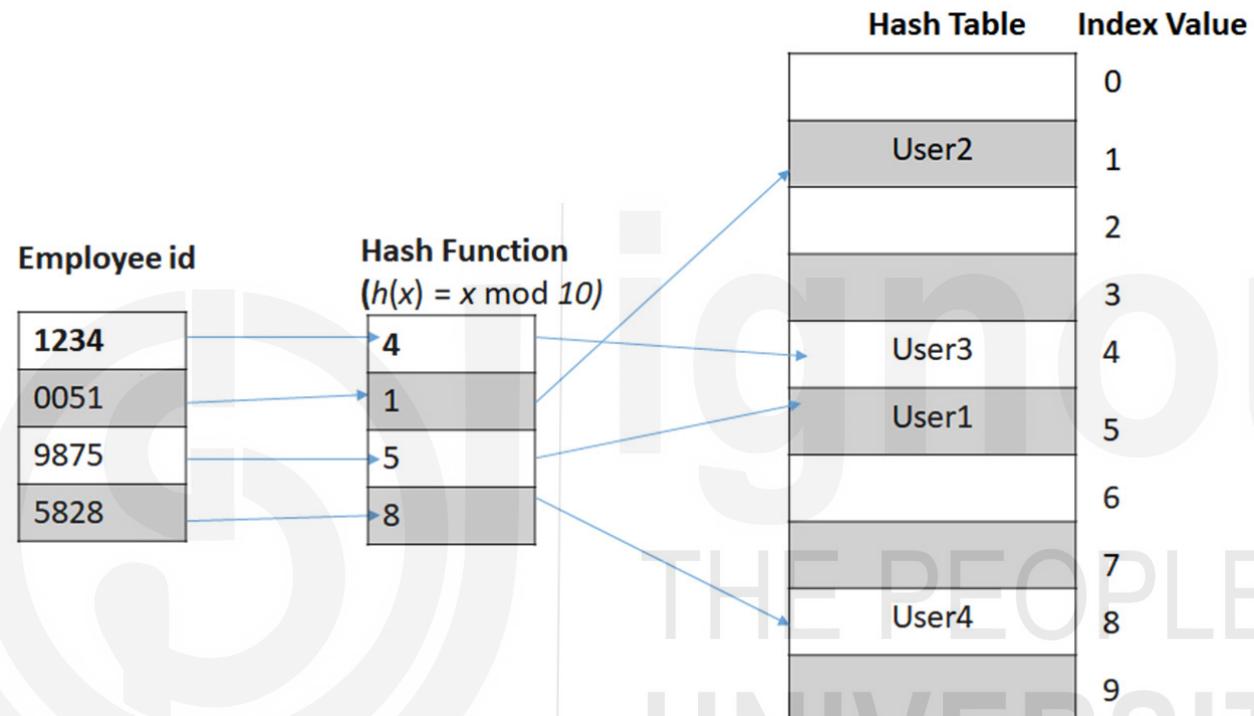


Figure 2 Hash Function and Hash Table

As we can see from Figure 2, instead of creating a huge hash table of size 9875, we have now managed to store the elements within an array of size 10. The hash function has converted the input into smaller set of keys that are used as index for the hash table.

Let us re-look at two challenges we saw in our earlier direct access method. The examples we discussed in Figure 2 use integer values as input keys. If we use non-integer values such as images or strings, we need to convert it first into a non-negative integer value. For instance, using the corresponding ascii values for each of its character, we can get a numeric value for a string. We can then use the hash function to create a fingerprint for the numeric value to store the corresponding details in the right sized hash table.

### 10.3.2 Hash Function

As we saw in the previous example, a hash function reduces a large non-negative integer into a smaller hash value which is used as an index into the hash table for searching the value.

The efficiency of a hash function is determined by following characteristics:

- **Computing efficiency** – The hash function should compute the hash value quickly and efficiently even for large key values
- **Uniform distribution** – The hash function should be able to distribute the keys evenly in the hash table.
- **Deterministic** – The hash function should consistently create the same key for a given value.
- **Minimal Collisions** – The hash function should minimize the key collisions in the hash table.

### 10.3.3 Simple Hash Example

Let us look at implementation of main functions using a modulo-based hash function.

We assume no collisions for this sample code in Java.

```
// the function returns the stored value for the input key
public V getValue(int inputKey) {
    int hashvalue = getHashValue(inputKey);
    return this.hashArray[hashvalue].value;
}

//the function adds the value for the given input key
public void addValue(int inputKey V inputValue) {
    int hashvalue = getHashValue(inputKey);
    this.hashArray[hashvalue].value = inputValue ;
}

//the function computes the hash value using mod logic
public int getHashValue(int inputKey) {
    return inputKey % this.hashArray.length;
}

//the function removes the input value from the hashArray
public void removeValue(int inputKey) {
    int hashvalue = getHashValue(inputKey);
    this.hashArray[hashvalue].value = null;
}
```

## 10.4 COLLISION RESOLUTION

For large set of input keys, we might end up having same hash value for two different input values. For instance, let us consider our simple hash function  $h(x) = x \bmod 10$

As the hash function provides the remainder value, if we have two input keys 24 and 4874, the hash value will be 4. These cases cause collision as both the input keys 24 and 4874 compete for same slot in the hash table.

We discuss three key collision resolution techniques in subsequent sections.

### 10.4.1 Separate Chaining

In separate chaining method, we chain the values to the same spot in the hash table. We use a data structure like linked list that can store multiple values.

The example Figure 3 depicts collision handling using the modulo based hash function. The input values 0051 and 821 result in the same hash value of 1. In the hash table we chain the values for user 2 and user 5 for the same slot.

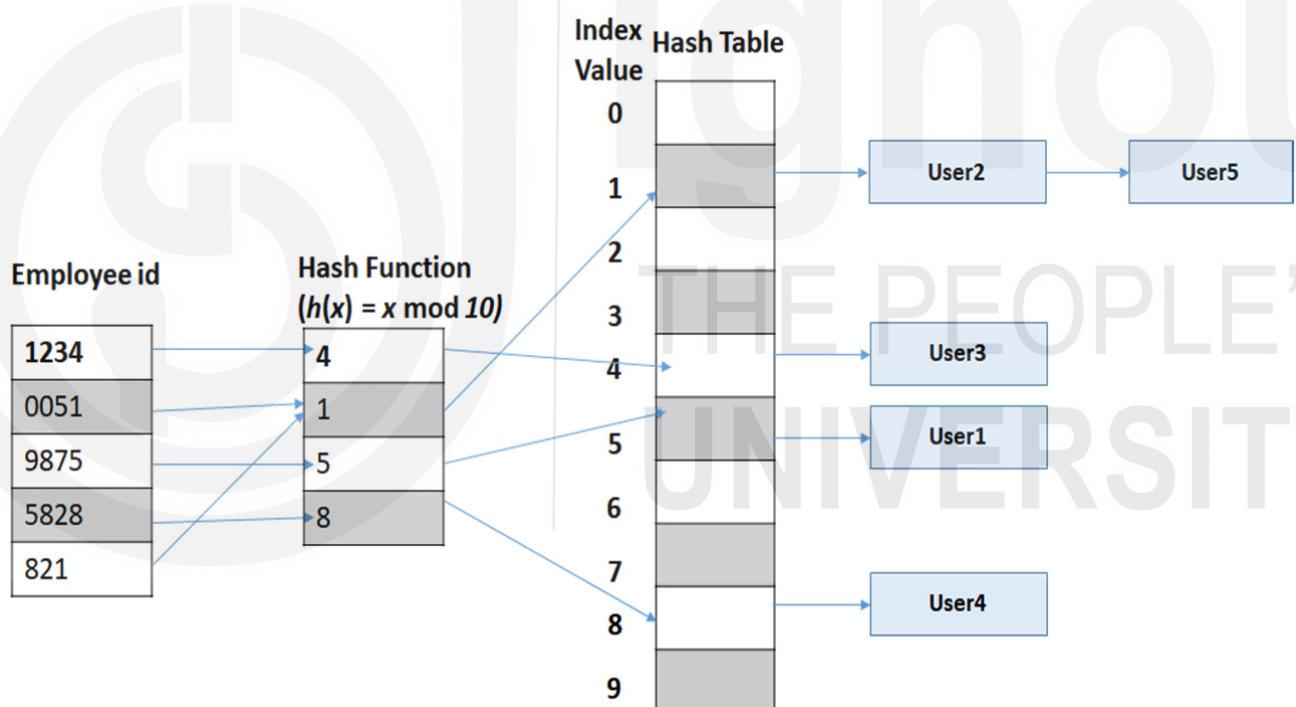


Figure 3 Separate Chaining

We are chaining the data values user2 and user5 for the slot 0 in the hash table.

#### Insert Operation

Given below are the steps for the insert operation using separate chaining method to insert a key k:

1. Compute the hash value of the key k using the hash function.
2. Use the computed hash value as the index in the hash table to find the slot for the key k.
3. Add the key k to the linked list at the slot.

### **Search operation**

Given below are the steps for the search operation for key k:

1. Compute the hash value of the key k using the hash function.
2. Use the computed hash value as the index in the hash table to find the slot for searching the key k.
3. Check for all elements in the linked list at the slot for a match with key k.

### **Check Your Progress – 1**

1. \_\_\_\_\_ provides direct mapping of keys to the hash table index.
2. The two key challenges with index mapping are \_\_\_\_\_.
3. The main characteristics of a hash function are \_\_\_\_\_.
4. The time complexity of index mapping is \_\_\_\_\_.
5. \_\_\_\_\_ data structure can be used to chain multiple values to the same spot in the hash table.
6. Hash value should always be non-negative. True/False

#### **10.4.2 Open Addressing**

In the open addressing collision addressing strategy, we search for the next available slot in the hash table when the natural slot is not available. We search for the open or unused locations in the hash table.

There are mainly two variants of open addressing – linear probing and quadratic probing. In the linear probing we sequentially iterate to the next available spot.

We define the linear probe by the following equation for  $i^{\text{th}}$  iteration:

$$h(x, i) = (h(x) + i) \bmod m \text{ where } m \text{ is the hash table size}$$

We need to accordingly change the other hash functions such as `getHashCode`, `putHashCode` and `deleteHashCode`.

- For `getHashCode` we need to start from the initial slot (`hashTable[h(x)]`) we need to check the subsequent slots till we find the matching key.
- For `putHashCode` we need to start with the initial slot (`hashTable[h(x)]`) till we find an empty slot or till the hashtable is full.
- For `deleteHashCode` we can place null into the slot or use an availability marker (occupied, available).

The linear probing leads to a situation known as “primary clustering” wherein the consecutive slots form “cluster” of keys in the hash table. As the cluster size grows, it impacts the efficiency of the probing for placing the next key.

Quadratic probing makes larger jumps to avoid the primary clustering. We define the quadratic probe by the following equation for  $i^{\text{th}}$  iteration:

$$h(x, i) = (h(x) + i^2) \bmod m$$

As we can see in the equation, for every iteration the quadratic probing makes larger jumps. In Quadratic probing we encounter “secondary clustering” problem.

Let us look at an example for linear probing to avoid the collision. Let us consider the following set of keys [56, 1072, 97, 84, 60] and the hash table size of 5. When we apply mod based hash function and start placing the keys in the appropriate slots we get the placement as depicted in Figure 4.

| Index | Hash Table |
|-------|------------|
| Value |            |
| 0     | 60         |
| 1     | 56         |
| 2     | 1072       |
| 3     | 97         |
| 4     | 84         |

Figure 4 Linear Probing

The value 56 goes to position 1 due to the mod value of  $(56 \bmod 5)$  operation. Similarly, 1072 assumes position 2. However, when we try to place the next element 97 we end up with a collision at slot 2. So, we find the next empty slot at slot 3 and place 97 there. Rest of the elements 84 and 60 go to the positions 4 and 0 respectively based on their mod values.

#### 10.4.3 Double Hashing

We can avoid the challenges with primary clustering and secondary clustering using the double hashing strategy. Double hashing uses a second hash function to resolve the collisions. The second hash function is different from the primary hash function and uses the key to yield non-zero value.

The first hash function in the double hashing finds the initial slot for the key and the second hash function determines the size of jumps for the probe. The  $i^{\text{th}}$  probe is defined as follows

$$h(x,i) = (h_1(x) + i * h_2(x)) \bmod m \text{ where } m \text{ is the hash table size}$$

Let us look at an example for the double hashing to understand it better. Let us consider a hash table of size 5 and we use the below given hash functions:

$$H_1(x) = x \bmod 5$$

$$H_2(x) = x \bmod 7$$

Let us try to insert two elements 60 and 80 into the hash table. We can place the first element 60 at slot 0 based on the hash function. When we try to insert the second element 80, we face a collision at slot 0. For the first iteration we apply the double hashing as follows:

$$H(80,1) = (0+1*3) \bmod 5 = 3$$

Hence, we now place the element 80 in slot 3 to avoid collision as depicted in figure 5.

| Index | Hash Table |
|-------|------------|
| Value |            |
| 0     | 60         |
| 1     |            |
| 2     |            |
| 3     | 80         |
| 4     |            |

Figure 5 Double Hashing Example

## 10.5 COMPARISON OF COLLISION RESOLUTION METHODS

Comparison of linear probing, quadratic probing and double hashing is given below:

| Collision Resolution Technique | Separate Chaining          | Open Addressing - Linear Probing | Open Addressing - Quadratic Probing | Double Hashing    |
|--------------------------------|----------------------------|----------------------------------|-------------------------------------|-------------------|
| Primary clustering             | No                         | Yes                              | No                                  | No                |
| Secondary clustering           | No                         | No                               | Yes                                 | No                |
| Key storage in Hash table      | Inside & Outside Hashtable | Inside Hash table                | Inside Hash table                   | Inside Hash table |
|                                |                            |                                  |                                     |                   |

## 10.6 LOAD FACTOR AND REHASHING

The hash table provides constant time complexity for operations such as retrieval, insertion and deletion with lesser keys. As the key size grows, we run out of vacant spots in the hash table leading to collision that impacts the time complexity. When the collision happens, we need to re-adjust the hash table size so that we can accommodate additional keys. Load factor defines the threshold when we should resize the hash table to main the constant time complexity.

Load factor is the ratio of the elements in the hash table to the total size of the hash table. We define load factor as follows:

$$\text{Load factor} = (\text{Number of keys stored in the hash table}) / \text{Total size of the hash table.}$$

In open addressing as all the keys are stored within the hash table, the load factor is  $\leq 1$ . In separate chaining method as the keys can be stored outside the hash table, there is a possibility of load factor exceeding the value of 1.

If the load factor is 0.75 then as soon as the hash table reaches 75% of its size, we increase its capacity. For instance, lets consider the hash table of size 10 with load factor of 0.75. We can insert seven hash keys into this hash table without triggering the re-size. As soon as we add the eighth key, the load factor becomes 0.80 that

exceeds the configured threshold triggering the hash table resize. We normally double the hash table size during the resize operation.

### 10.6.1 Rehashing

when the load factor exceeds the configured value, we increase the size of hash table. Once we do it we should also re-compute the hash values for the existing keys as the size of the hash table has changed. This process is called “rehashing”. Rehashing is a costly exercise especially if the key size is huge. Hence it is necessary to carefully select the optimal initial size of the hash table to start with.

Given below are the high-level steps for rehashing:

1. For each new key insert into the hash table, compute the load factor
2. If the load factor exceeds the pre-defined value then increase the hash table size (normally we double the hash table size)
3. Recompute the hash value (rehash) for each of the existing elements in the hash table.

Let us look at the rehashing with an example. We have a hash table of size 4 with load factor of 0.60. Let's start by inserting these elements – 30, 31 and 32. We can insert 30 at slot 2 and 31 at slot 3 and 32 at slot 0. Insertion of 32 triggers the hash table resize as the load factor has breached the threshold of 0.60. As a result, we double the hash table size to 8.

With the new hash table size, we need to recalculate the hash values of the already inserted keys. Key 30 will now be placed in slot 6, key 31 will be placed in slot 7 and key 32 in slot 0.

### ☞ Check Your Progress – 2

1. The main techniques of open addressing are \_\_\_\_\_
2. Load factor triggers \_\_\_\_\_
3. Linear probing leads to \_\_\_\_\_ clustering
4. \_\_\_\_\_ probing make large jumps leading to secondary clustering
5. Second hash function in double hashing can result in 0. True/False
6. \_\_\_\_\_ should be done for the existing keys of the hash table post resizing.

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## 10.7 SUMMARY

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In this unit, we started discussing the main motivations for the hashing. Hashing allows us to store and retrieve large data efficiently.

Index mapping uses the input values as direct index into the hash table. Index mapping requires huge hash table size leading to inefficiencies. When we handle large size input values we encounter collision where multiple input values compete for the same spot in the hash table. The main collision resolution techniques are separate chaining and open addressing. In separate chaining we chain the values that get mapped to a spot. We use linear probing and quadratic probing as part of open addressing technique to find the next available spot. We use two hash functions as part of double hashing. Load factor determines the trigger for the hash table resizing and once the hash table is resized, we re-compute the hash values of the existing keys using rehashing.

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## 10.8 SOLUTIONS/ANSWERS

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**☞ Check Your Progress – 1**

1. Index mapping
2. handling non integer keys and large hash table size
3. computing efficiency, uniform distribution, deterministic and minimal collisions
4.  $O(1)$
5. Linked List
6. True

**☞ Check Your Progress – 2**

1. linear probing, quadratic probing and double hashing
2. resizing of hash table
3. primary
4. quadratic
5. False
6. Rehashing

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## 10.9 FURTHER READINGS

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<https://ieeexplore.ieee.org/book/8039591>

# UNIT 11 ADVANCED DATA STRUCTURES

## Structure

|        |                                                |
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| 11.0   | Introduction                                   |
| 11.1   | Objectives                                     |
| 11.2   | Brief Introduction to Binary Search Tree (BST) |
| 11.3   | Scapegoat trees                                |
| 11.3.1 | Operations on Scapegoat tries                  |
| 11.4   | Tries                                          |
| 11.4.1 | Binary Tries                                   |
| 11.5   | X-fast Tries                                   |
| 11.5.1 | Operations on X-fast tries                     |
| 11.6   | Y-Fast Tries                                   |
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## 11.0 INTRODUCTION

In this unit we discuss various kinds of trie data structure. For efficient searching the data we use the trie. We shall closely look at various operations such as search, insert, delete, successor and predecessor on the trie data structure. We also look at optimizing the time complexity in the trie data structure.

## 11.1 OBJECTIVES

After going through this unit, you should be able to

- understand key concepts of scapegoat tries,
- understand tries and binary tries,
- understand key concepts of x-fast tries and y-fast tries

## 11.2 BRIEF INTRODUCTION TO BINARY SEARCH TREE (BST)

In this unit we discuss the Tries that are type of binary search trees. So, we briefly discuss the binary search tree. Binary search tree is a sorted tree that stores the keys in ordered way. For any given node in the binary search tree, the keys in left side is lesser than keys in the right side.

As the binary search tree is sorted, the data structure is useful for searching and sorting the data. To search for a key in the BST, we start from root node and if the search key is less than root node we check for left node else we check the right node. We recursively search for the key till we exhaust the nodes. To find the successor of the key k, we find the smallest key that is greater than k and for finding the predecessor for key k, we find the largest key that is smaller than k. The complexity of BST for search, insert and delete is O(n) where n is the number of nodes in the tree.

## 11.3 SCAPEGOAT TRIES

The scapegoat tries are self-balancing binary search tree that provides the worst-case performance of  $O(\log n)$  for search and  $O(\log n)$  amortized time for insert and delete operation.

We say that the binary search tree is balanced when the weight of the left nodes matches the weight of the right nodes. We define the  $\alpha$ -weight-balanced tree by the below-given equation:

$$\begin{aligned} \text{Size}(\text{left}[x]) &\leq \alpha * \text{size}(x) \text{ and} \\ \text{Size}(\text{right}[x]) &\leq \alpha * \text{size}(x) \end{aligned}$$

Where

- $0.5 \leq \alpha < 1$
- X is the node of the tree and  $\text{left}(x)$  is the left child of x and  $\text{right}(x)$  is the right child of x.
- The size (x) is defined as number of keys stored in the sub-tree of x including the key stored at x.

Figure 1 provides the scapegoat tree that is  $\alpha$ -weight-balanced

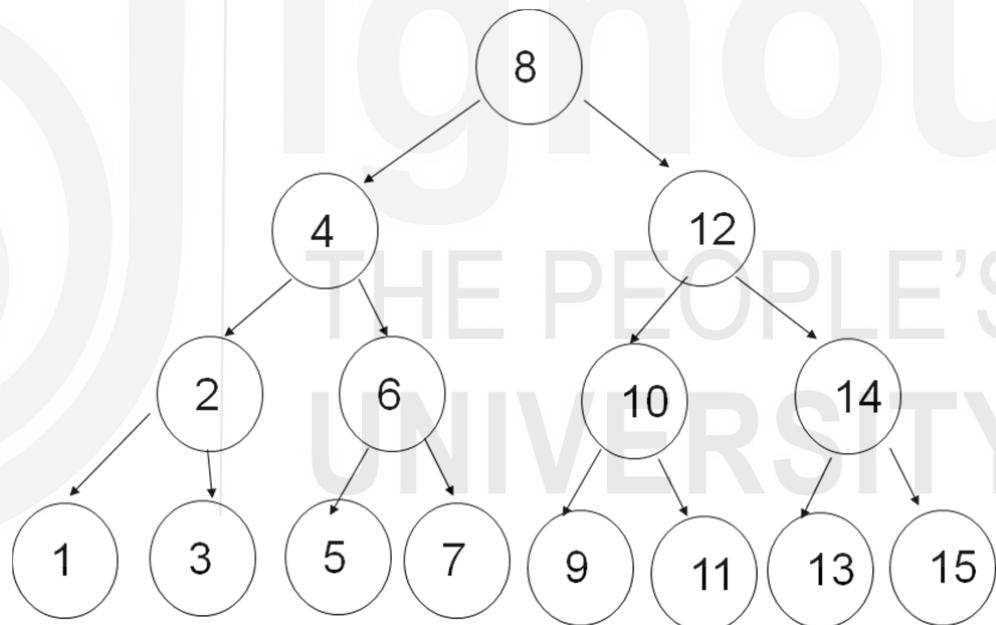


Figure 1 Sample Scapegoat tree

### 11.3.1 Operations on Scapegoat tries

In this section we define various operations on Scapegoat tries.

#### Search Operation

The search operation is similar to that of the binary search tree.

#### Insert Operation

For inserting a new node into the tree, we will find a scapegoat node. Given below are the steps to find the scape goat node for inserting a new value Y into the tree:

1. Create the new node x and insert in natural way

- Walk up the tree hierarchy to find the scapegoat node that is not  $\alpha$ -weight-balanced. If  $X_i$  is the node that is not  $\alpha$ -weight-balanced, we compute the size of as follows:

$$\text{Size}(X_{i+1}) = \text{Size}(X_i) + \text{size}(\text{brother}(X_i)) + 1$$

Where  $\text{brother}(X_i)$  is the other child of  $X_i$ 's parent or null if another child does not exist

Let us look at an insert example where we try to insert element 4.5 into a tree as depicted in Figure 2.

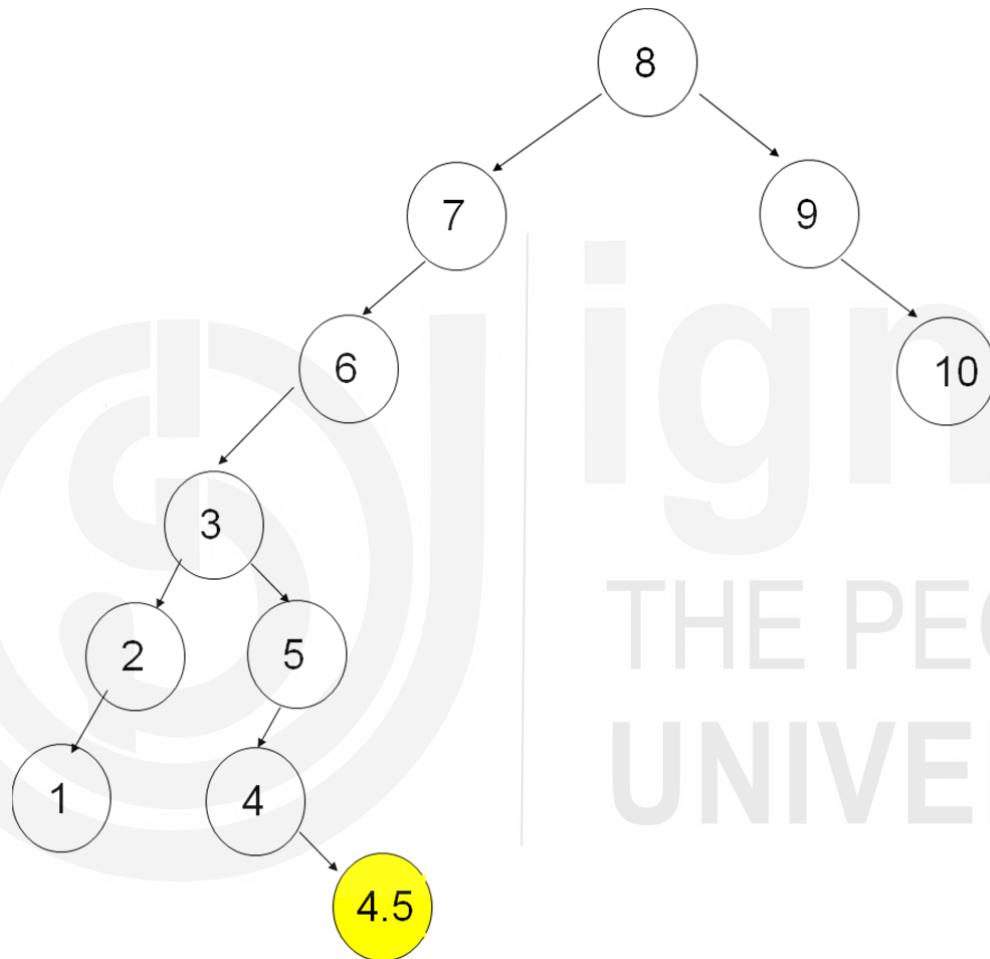


Figure 2 Inserting new node to Scapegoat tree

If we traverse the tree to find the scapegoat node that is not load balanced we reach, node with key 6. So, we balance the tree at node 6. The balanced tree is depicted in Figure 3.

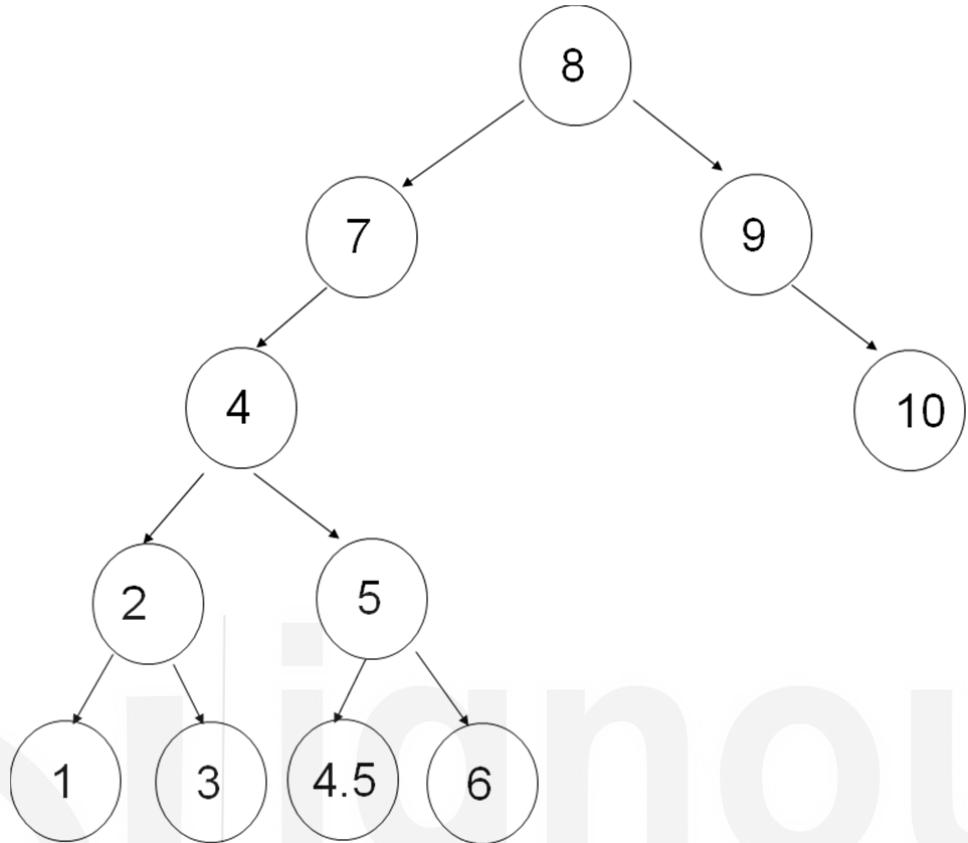


Figure 3 New scapegoat tree rebalanced after inserting

### Delete operation

Given below are the steps for deleting the node x:

1. If the node x is a leaf node, we can delete it.
2. If the node x has single left child or single right child, we replace x with its only child.
3. If the node x has both left child and right child, we find the lowest value node in the right sub-tree and replace x with it.

### Check Your Progress – 1

1. The scapegoat tries are \_\_\_\_\_ binary search tree.
2. For inserting the node we find the \_\_\_\_\_ node
3. The worst-case performance of scapegoat search operation is \_\_\_\_\_
4. In the binary search tree, the left node value is \_\_\_\_\_ than right node value
5. The complexity of BST for search, insert and delete is \_\_\_\_\_

## 11.4 TRIES

Tries are tree-based data structure that are used to search for string-based keys in a given set. We use individual characters of a string as edges that connect the nodes of the tree. Given below are the main characteristics of tries:

1. The child nodes of a node are associated with a common prefix.
2. The key is denoted by the position of the node
3. String search can be done by using the depth-first search.

There are many real-world use cases that involve integer-based information retrieval. For instance, id number-based information retrieval, account number-based search all need integer-based lookup. For such use cases we can use bitwise tries for faster information retrieval. Tries are also used in web search engines, for text search use cases.

The average time complexity for search, insert and delete operations for trie data structure is  $O(n)$ .

Figure 4 depicts a sample Trie

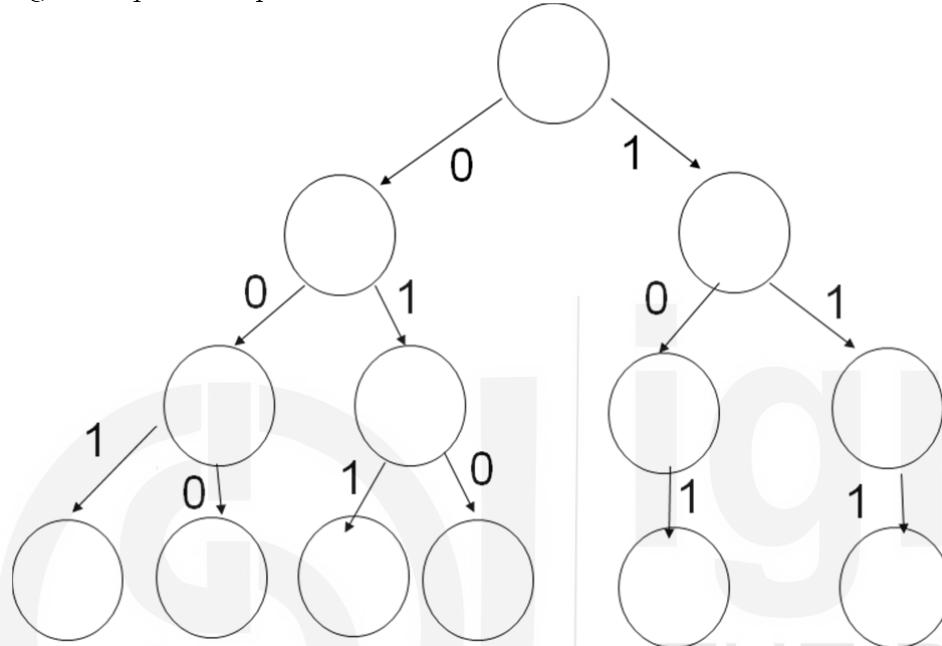


Figure 4 Sample Trie

#### 11.4.1 Binary tries

The binary tries use bits as keys that can be used to represent integer. We can use the bit representation of individual characters of a string which can then be used to traverse the binary Tries. In the binary trie only the leaf node holds the key. We compare the bits of the tree to find the key.

#### Search operation in Binary trie

Given below are steps for searching for a key in binary trie:

1. Start the search with root node
2. Initialize  $i=0$  and compare the  $i^{\text{th}}$  bit of key.
3. If the key bit value is 0 check the left node, else search the right node.
4. If the current node is leaf and if all the bits of the key match the path, return success else return failure
5. If the current node is not leaf increment the counter  $i$  and repeat the steps 3 through 5.

#### Insert operation in Binary Trie

We insert the keys based on their bit values. The initial 0 bit will go to left and 1 bit to the right. We follow the process till all the bits in all keys are inserted.

Given below are the steps for insert operation:

1. Search for key  $k$  in the tree.

2. When the search failure happens on a non-leaf node, we simply link the non-leaf node to the new node
3. If the search failure happens on leaf node, we create a new internal node to accommodate the new key and existing key.

### Delete operation in Binary Trie

Given below are the steps for deleting the node x:

1. Search for node x in the tree. When the leaf node x is reached, it is deleted.
2. We traverse back in the search path for x deleting the nodes until we reach a node u that has child not in the search path for x.
3. We traverse back to the root node deleting the descendent pointer to node x.

Figure 5 is an example of inserting the following keys:

S 01001  
M 11001  
U 00110

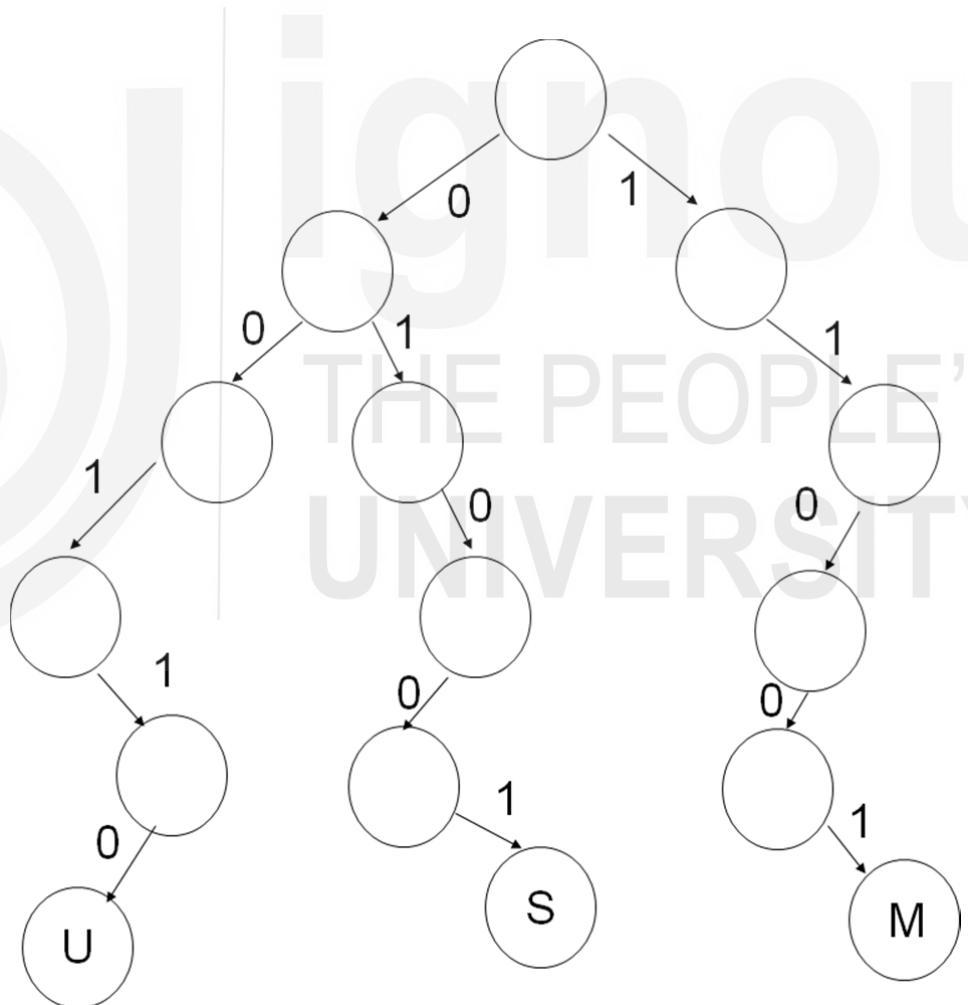


Figure 5 Binary Trie with keys inserted

As we can notice in Figure 5, the keys in left subtree are smaller when compared to keys in the right subtree for any given node.

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## 11.5 X-FAST TRIES

X-fast tries are bitwise tries that stores the integers from a bounded domain. The complexity of successor operation is  $O(\log \log M)$  where  $M$  is the domain's maximum value; find operation is  $O(1)$ ; insert and delete operation is  $O(\log M)$  where  $M$  is the domain's maximum value. The subtree uses a common prefix from its parent node. The leaf node represents values from 0 to  $M-1$  where  $M$  is the domain's maximum value.

The left child adds 0 to the prefix and the right child adds 1 to the prefix.

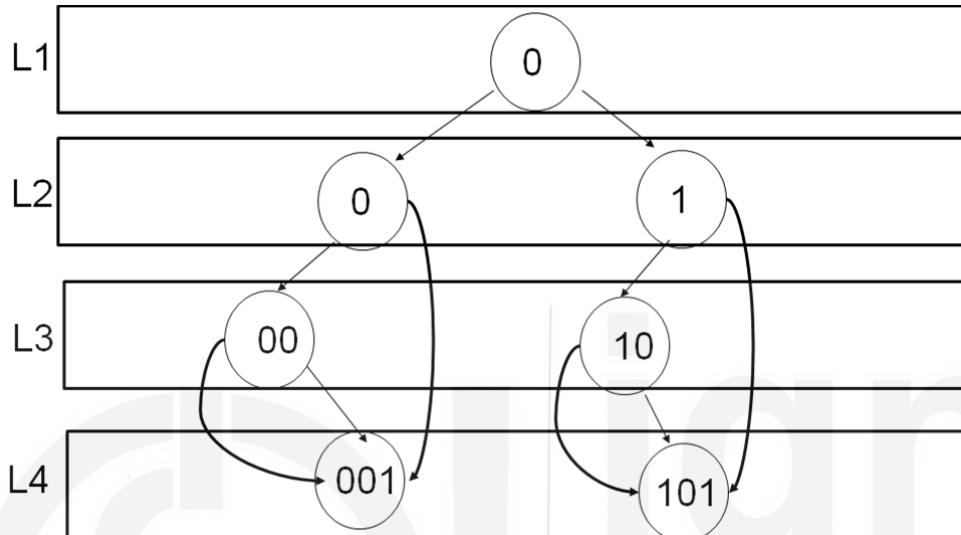


Figure 6 X-fast trie

We have depicted a four-level x-fast trie in Figure 5. Each level of the x-fast trie is implemented as hash table. The internal nodes are represented only if their subtree has one or more leaf nodes. If the internal node does not have a left child, then the left pointer points to the smallest leaf node in the right subtree which is called descendant pointer.

The tree depicted in Figure 5 has domain size of 8 from 0 to 7. We store the nodes 0 (001) and 5 (101).

### 11.5.1 Operations on X-fast tries

In this section we shall look at the main operations on X-fast tries

#### Find operation

For finding value of key  $k$ , we can look up the hash table indexing the leaf nodes. This is a constant time operation.

#### Successor and Predecessor

To find the successor of key  $k$ , we follow these steps:

1. Using the prefix of key, we perform the binary search by querying the hash table to find the lowest ancestor of  $k$ .
2. Once we get a match we use the descendant pointer of  $k$
3. For the predecessor use the previous leaf and for successor use the next leaf.

**Insert Operation**

To insert key k with value v, we follow these steps:

1. Find the predecessor and success or k
2. Create a new leaf node between predecessor and successor of K and point it to v.
3. Start traversing the tree from the root to leaf and create the missing internal nodes and adding the descendant pointers wherever necessary.

**Delete Operation**

To delete the key k, we follow these steps:

1. Remove the k from the hash table indexing the leaf nodes.
2. Delete the k node and link its predecessor and successor.
3. Traverse the tree from the root and delete the internal nodes that have k as only nodes within its subtrees and update the descendant pointers appropriately.

## 11.6 Y-FAST TRIES

Y-fast tries are bitwise tries that store integers from bounded context. They are the improved version of X-fast tries that optimize the memory. Similar to the X-fast tries, all subtrees will have a common prefix of its parent.

The complexity of successor operation is  $O(\log \log M)$  where M is the domain's maximum value; find operation is  $O(1)$ ; insert and delete operation is  $O(\log M)$  where M is the domain's maximum value.

The Y-fast trie consists of two data structures – X-fast trie at the top and the balanced binary search tree in the bottom. We have depicted the Y-fast Trie in Figure 6.

We chose a representative r from the binary search tree and store it in the X-fast trie. The r value should be smaller than its successor in the X-fast trie.

One of the main differences between X-fast trie and Y-fast trie is that in the Y-fast trie, the X-fast trie operates on the representatives of the binary search tree. The leaf node point to the binary search tree.

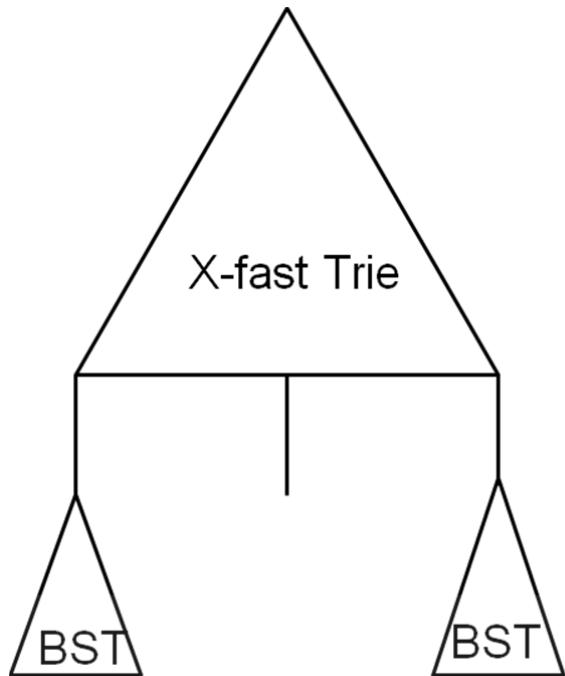


Figure 7 Y-fast Trie

### 11.6.1 Operations on Y-fast tries

In this section we shall look at the main operations on Y-fast tries.

#### Find operation

Given below are the steps to find the key k:

1. Find the successor and predecessor of k in the X-fast trie. We can do this by finding the smallest representative  $r$  that is greater than k and largest representative  $r^l$  that is smaller than k in the X-fast trie.
2. We carry out the binary search for k in the binary search trees represented by  $r$  and  $r^l$

#### Successor and Predecessor

1. To find successor of k, search for smallest representative  $r$  in the X-fast trie.
2. Find the predecessor of  $r$  in X-fast trie.
3. Search for the binary trees pointed by these two representatives for getting the successor of k.

#### Insert Operation

To insert the key k, given below are the steps:

1. Insert the key to the tree that has the successor of k.
2. Point the node to v
3. If the tree contains more than  $2 \log U$  elements (where U is the maximum value of the domain), then remove it representative from the X-fast trie. Split the binary search tree into two and add the representatives from each of the binary search tree into the X-fast trie.

#### Delete operation

Given below are the steps for deleting the key k:

1. Delete the key k from the tree

2. If the elements in the tree drop below  $(\log U)/4$  (where  $U$  is the maximum value of the domain), merge the tree with its predecessor or successor. Remove the representatives of the merged trees from the X-fast trie.
3. Add the representative of the new tree into X-fast trie.
4. If the newly-formed tree contains more than  $2 \log U$  elements (where  $U$  is the maximum value of the domain), then remove its representative from the X-fast trie. Split the binary search tree into two and add the representatives from each of the binary search tree into the X-fast trie.

### Check Your Progress – 2

1. The child nodes of a node in a Trie are associated with a \_\_\_\_\_
2. The average time complexity for search, insert and delete operations for trie data structure is \_\_\_\_\_
3. The binary tries use \_\_\_\_\_ as keys that can be used to represent integer
4. X-fast tries are bitwise tries that stores the integers from a \_\_\_\_\_
5. Each level of the x-fast trie is implemented as \_\_\_\_\_
6. Y-fast tries are the improved version of \_\_\_\_\_

## 11.7 SUMMARY

In this unit, we started discussing the key aspects of binary search tree. Binary search tree is a sorted tree that stores the keys in ordered way. The scapegoat tries are self-balancing binary search tree. When the weight of the left nodes matches the weight of the right nodes then we say that the binary search tree is balanced. To insert the data we find the scapegoat node in scapegoat trees and balance the tree around it. Tries are tree-based data structure that are used to search for string-based keys in a given set. The average time complexity for search, insert and delete operations for trie data structure is  $O(n)$ . The binary tries use bits as keys that can be used to represent integer. X-fast tries are bitwise tries that stores the integers from a bounded domain.

## 11.8 SOLUTIONS/ANSWERS

### Check Your Progress – 1

1. Self-balancing
2. scapegoat
3.  $O(\log n)$
4. Lesser
5.  $O(n)$

### Check Your Progress – 2

1. common prefix
2.  $O(n)$
3. bits
4. bounded domain
5. hash table

## 11.9 FURTHER READINGS

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# UNIT 12 FILE STRUCTURES

## Structure

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| 12.4   | Sequential files                                         |
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| 12.6   | Indexed Sequential File Organization                     |
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| 12.8   | Solutions/Answers                                        |
| 12.9   | Further Readings                                         |

## 12.0 INTRODUCTION

The data is stored and organized through file structure. Software applications and platforms store the data in files. Operating systems manage critical configuration through file and even databases also store the data in files such as transaction logs. Files essentially serve as the key building blocks for data organization. We can enforce governance such as data integrity checks, security rules, access controls, sharing controls for files.

In this unit we discuss various aspects of file such as file organization, file types and related concepts.

## 12.1 OBJECTIVES

After going through this unit, you should be able to

- understand key concepts of files,
- understand the file organization concepts,
- understand sequential files and direct file organization,
- Understand indexed file organization and indexed sequential files

## 12.2 BASIC CONCEPTS OF FILE

A file is a collection of data records. The key operations of the file are as follows:

- File creation when the file gets created initially.
- File update when we update the file with new data records or modify existing data records.

## File Structures

- File deletion when we delete the file
- File merging that combines the content of multiple files into a single file.
- File searching that involves searching for a specific data record in a file.

A data record in a file encapsulates the data of a single entity. For instance, an employee data record captures details of a single employee such as employee id, employee name, employee address, employee phone number and employee date of join.

Each data record is uniquely identified by a key. For instance, in the employee data record, employee id is the key.

The table 1 provides the employee data records in an organization:

| Employee Number | Employee Name | Employee Address | Department  | Date of Join |
|-----------------|---------------|------------------|-------------|--------------|
| 45278           | Employee 1    | Kanpur           | Sales       | 01-Jan-2020  |
| 167352          | Employee 2    | Mysore           | Development | 01-Mar-2020  |

## 12.3 FILE ORGANIZATION

File organization defines the way the data record is stored and retrieved from the files. File organization provides the data record relationship specifying how the data records are mapped to the disk blocks. We can either store fixed length record in the files or use flexible file structure to support data records of varying length.

There are multiple ways of file organization such as sequential, direct, indexed sequential and others. We can select the file organization type based on the use case, information retrieval performance, ease of information management and others.

Given below are the most commonly used file organizations:

- Sequential files – The data records are stored in a pre-defined order. For instance, the data records are sequenced based on the key values. In this file organization type we need to sequentially access the record.
- Relative files – The data record is stored at a fixed location that can be accessed using a static key value. As we can access the data record using a fixed value, we can retrieve or insert the data record randomly in this file organization type.
- Direct files – Similar to the relative file that supports non-integer key value.
- Indexed sequential files – In this file organization we add an index to provide the random access to the sequential files.
- Indexed files – The data records are indexed to improve the performance of the data retrieval.

Figure 1 provides various file organizations that are most commonly used.

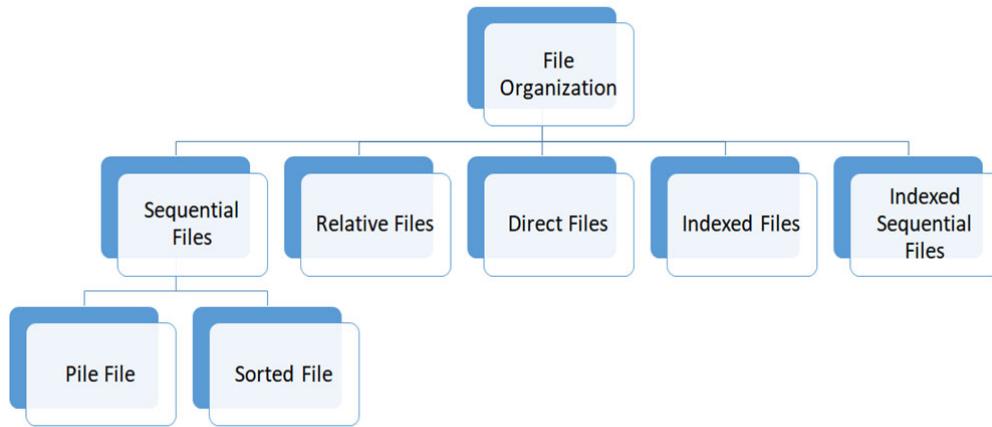


Figure 1 Types of File organizations

### 12.3.1 Key drivers for file organization

Given below are the main drivers for the file organization:

- File organization helps in optimal design of file records so that they can be retrieved as quickly as possible.
- Improve the performance of file operations such as insert, update and delete.
- Ensure the data consistency and avoid duplicates during file operations.
- Provide optimal storage for managing the files.

## 12.4 SEQUENTIAL FILES

We write the data records in a specific sequence in sequential files. The data is also accessed in the order it is written to the physical device. We usually order the data records based on the key value. In Sequential files the reading happens from the beginning of the file and write happens at the end of the file.

The legacy storage systems such as tape storage use sequential files.

### 12.4.1 Operations on sequential files

We discuss the main operations on the sequential files:

#### Insert operation

As the sequential files are organized based on their keys, when we insert we should find the exact position of the new key value and insert the key over there.

If there are multiple insertions, we can batch them to optimize the performance optimization. We can collect all the new inserts into transaction log and then sort the new keys in order in the transaction log. We can then merge the entries in the transaction log into the main file in batch mode.

#### Delete Operation

In the delete operation, we need to reclaim the space from the deleted record. Here as well we can use the concept of transaction log for performance optimization. We can add the delete marker for the key position in the transaction log and later we can merge the changes to the main file in batch mode. During merge operation, we drop the data records in the main file based on the marker.

#### Update Operation

## File Structures

For performing the update operation, we need to add the delete marker for the corresponding key and then insert the new data record for the corresponding key in the transaction log. Like always we merge the transaction log to the main file

### Retrieval Operation

We read the data record based on its key. For stale data reads, we can directly read the data record for the key from the main file. To maintain read consistency, we need to check If there are any pending updates in the transaction log and if so we need to merge the changes (deletion/insertion).

### **12.4.2 Types of sequential files**

There are mainly two types of sequential files – Pile files and sorted files.

#### Pile Files

In Pile files, the data records are inserted in the order of their arrival. For instance, let's consider the below given incoming Data records –

DR1, DR3, DR5, DR2

The data records are inserted as given in Figure 2:



Figure 2 Pile File

For searching the records, the file is searched from the beginning till the desired record is found. For deleting a record, we search for the record and add a deletion marker for the found record.

For inserting a new record, it will be done at the end of the file. The new record DR4 is to be inserted as shown in Figure 3



Figure 3 Pile File Insertion

#### Sort Files

In case of sort files, the data records are sorted based on the key and are inserted into the file.

For instance, let's consider the below given incoming Data records –

DR1, DR3, DR5, DR2

The data records are inserted as given in Figure 4:



Figure 4 Sort File

While inserting a new record the key of the new record is sorted along with the existing records and then inserted. For instance when we try to insert the data record DR4, the sorted insert is depicted in Figure 5



Figure 5 Sort file insert

#### 12.4.3 Advantages and disadvantages of sequential files

In this section we discuss the main advantages and disadvantages of the sequential files.

##### Advantages

The main advantages of sequential files are as follows:

1. Simple and easy to implement
2. Provides best usage of the storage space.
3. Can be used for data archival needs.
4. The underlying storage systems provide low-cost storage option.
5. Can be stored in inexpensive device like tape device.

##### Disadvantages

The main disadvantages of the sequential files are as follows:

1. The update operation is costlier and time consuming.
2. The access speed is slow due to the sequential access.
3. It is not possible to directly access a given data record key.
4. All records should have uniform structure.
5. The insert time of sorted file is high.
6. Overall processing is slow.

#### 12.4.4 Use cases for sequential files

We generally use sequential files for long-term archival of data and for batch processing operations. We also use sequential access for storing large amount of data that tolerates slow retrieval time.

##### Check Your Progress – 1

1. A \_\_\_\_\_ in a file encapsulates the data of a single entity
2. Each data record is uniquely identified by a \_\_\_\_\_.
3. In \_\_\_\_\_ files, the data records are inserted in the order of their arrival.
4. For optimizing the performance, we get all the updates into a \_\_\_\_\_ and later merge it into main file.
5. The two types of sequential files are \_\_\_\_\_ and \_\_\_\_\_.
6. Define a data record for a typical university's student enrolment system.

## 12.5 DIRECT FILE ORGANIZATION

In the direct file organization, we directly access the file by its key. To enable this direct access, we need to map the key to the address where the data record is stored. Direct access is also known as random access. The file records are stored in direct access storage device (DASD) like hard disk, CD, magnetic disk. We randomly place the record throughout the hard disk.

We have depicted the direct file organization in Figure 6

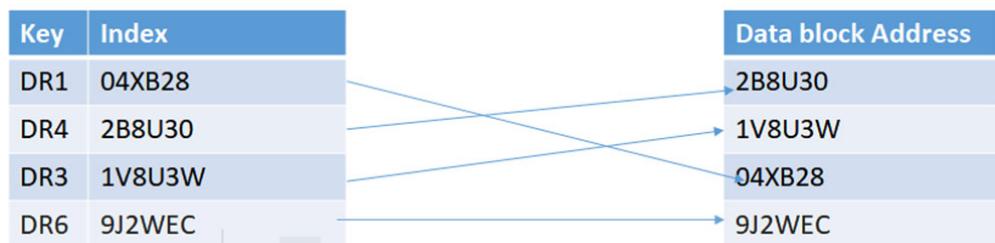


Figure 6 Direct File Organization

We use hash function to convert the key into the address. Naturally direct file access is faster compared to sequential files.

In direct file organization, the records are stored at a known addressed as depicted in Figure 6.

### 12.5.1 Hash Function and Collision Resolution

The most popular hash function is the modulo based function that computes the remainder value as the hash value based on the key. The hash value is then used to store the data record.

When there are huge set of keys, multiple keys will end up with same hash value leading to collision. In such cases, we use the collision resolution technique. The separate chaining technique chains the values to the same slot and open addressing technique probes for next available slot for placing the value.

### 12.5.2 Advantages and disadvantages of Direct file organization

We shall look at the main advantages and disadvantages of the direct file organization.

#### Advantages

Given below are the main advantages of direct file organization:

1. As we can directly access the data, the retrieval is fast that helps in transaction management systems such as relational database systems.
2. The insert, update and delete operations are faster.
3. The direct file organization is efficient in storage and retrieval of large data.
4. Key-based search is faster.
5. Can be used for real-time transactions that needs optimal performance.
6. Concurrent processing is possible

**Disadvantages**

Given below are the main disadvantages of direct file organization:

1. The required storage technology is costlier.
2. The usage of storage space is sub optimal.
3. Insert, delete and update needs update of the index table.

## 12.6 INDEXED SEQUENTIAL FILE ORGANIZATION

Indexed sequential file organization supports direct access of keys and also sequential access by keys.

We use the indexed sequential file organization for hierarchical data organization. For instance, let's consider a use case for retrieving the data record for the states. We use the indexed/direct file for getting the country. The country data record points to the sequential file storing the records of its constituent states. Indexed sequential files can be stored only on random access device such as magnetic disk.

To implement the indexed sequential file, we decouple the index and data files. The index file is structured hierarchically in tree structure whereas the data file stores the information sequentially.

We use two types of indexes static index and dynamic index.

We have depicted the indexed sequential file in Figure 7.

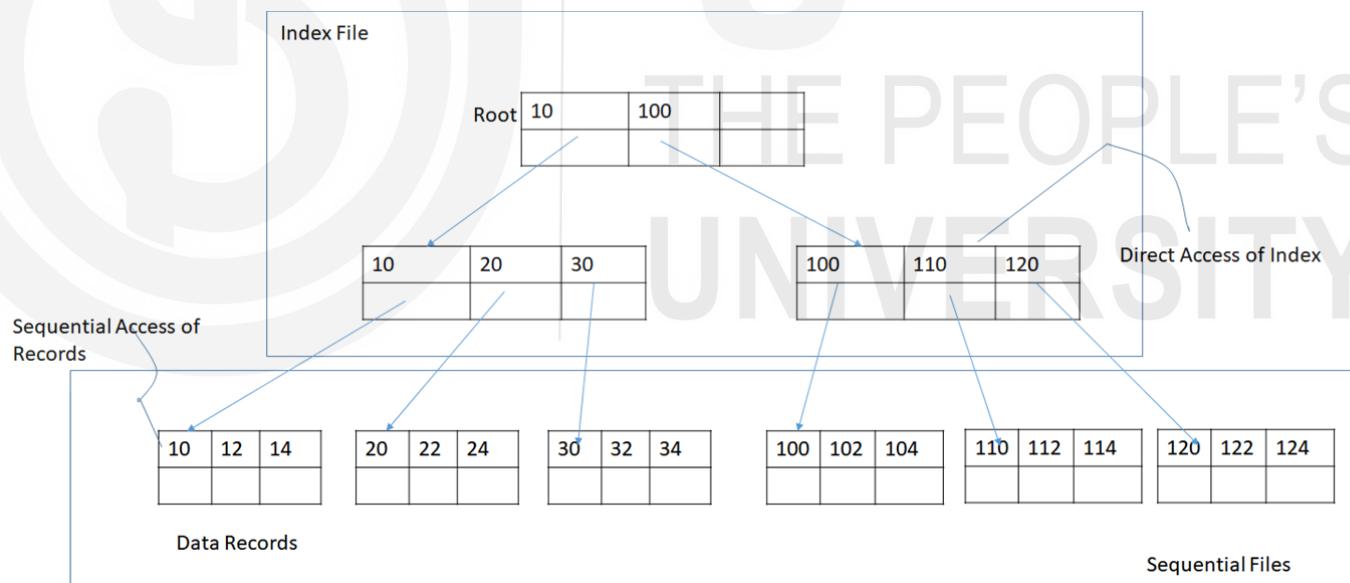


Figure 7 Indexed sequential file

As depicted in Figure 7, the indexed sequential file is depicted as a two-level hierarchy. The first level holds the index to each of the three records in the data file. The second level holds the sequential set of records.

The first level is accessed directly where we get the keys from the index file. In the second level we store the data record sequentially. As the data records are stored sequentially, the key in the first level just points to the first record in the second level from where it can be accessed sequentially.

When we have to insert the record, we update the data file based on the sequence and update the index accordingly. Static index and dynamic index are two main types of indexes. In static indexes the update to the records in the data file does not change the index structure whereas in the dynamic index, the updates to the data file changes the index structure.

### **12.6.1 Advantages and disadvantages of Indexed sequential file organization**

We shall look at the main advantages and disadvantages of the indexed sequential file organization

#### **Advantages**

Given below are the main advantages of indexed sequential file organization:

- As the records are directly accessed, the access speed is high
- Record insert is very fast.

#### **Disadvantages**

Given below are the main disadvantages of indexed sequential file organization:

- Usage of storage space is sub optimal
- The implementation is costly due to the required of costly hardware
- Extra storage for index file is required.

#### **☞ Check Your Progress – 2**

1. In the direct file organization, we directly access the file by its \_\_\_\_\_
2. The function that converts the key to address is called \_\_\_\_\_
3. The first level in the indexed sequential access is done \_\_\_\_\_ and second level is accessed \_\_\_\_\_
4. The data records in direct file organization are stored in \_\_\_\_\_ storage device
5. \_\_\_\_\_ file organization for managing hierarchical data

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## **12.7 SUMMARY**

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In this unit we mainly discussed about file organization and various types of file organization. A file is a collection of data records. The key operations of the file are File creation, file update, file deletion, file merging, file searching. File organization defines the way the data record is stored and retrieved from the files. We write the data records in a specific sequence in sequential files. There are mainly two types of sequential files - Pile Files and sort files. In Pile files, the data records are inserted in the order of their arrival. In case of sort files, the data records are sorted based on the key and are inserted into the file. In the direct file organization, we directly access the file by its key. Indexed sequential file organization supports direct access of keys and also sequential access by keys.

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## **12.8 SOLUTIONS/ANSWERS**

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#### **☞ Check Your Progress – 1**

1. Data record.

2. Key
3. Pile files
4. Transaction log
5. Pile files and sort files
6. A sample student enrollment structure is as follows:

Student Number, Student Name, Date of Enrollment, Address, Programme

### ☛ Check Your Progress – 2

1. Key
2. Hash function
3. Directly and sequentially
4. Direct access
5. Indexed sequential

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## 12.9 FURTHER READINGS

### References

- [https://en.wikipedia.org/wiki/File\\_system](https://en.wikipedia.org/wiki/File_system)
- [https://en.wikipedia.org/wiki/Sequential\\_access](https://en.wikipedia.org/wiki/Sequential_access)
- [https://en.wikipedia.org/wiki/Indexed\\_file](https://en.wikipedia.org/wiki/Indexed_file)
- <https://en.wikipedia.org/wiki/ISAM>

