

# **DESIGN AND ANALYSIS OF ALGORITHMS**

## **[R17A0508]**

### **LECTURE NOTES**

**B.TECH II YEAR – II SEM (R17)  
(2018-19)**



**DEPARTMENT OF  
COMPUTER SCIENCE AND ENGINEERING**

**MALLA REDDY COLLEGE OF ENGINEERING &  
TECHNOLOGY**

**(Autonomous Institution – UGC, Govt. of India)**

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Maisammaguda, Dhulapally (Post Via. Hakimpet), Secunderabad – 500100, Telangana State, India

**II Year B. Tech. CSE –II Sem**

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## **(R17A0508) DESIGN AND ANALYSIS OF ALGORITHMS**

### **Objectives:**

- To analyze performance of algorithms.
- To choose the appropriate data structure and algorithm design method for a specified application.
- To understand how the choice of data structures and algorithm design methods impacts the performance of programs.
- To solve problems using algorithm design methods such as the greedy method, divide and conquer, dynamic programming, backtracking and branch and bound.
- Prerequisites (Subjects) Data structures, Mathematical foundations of computer science.

### **UNIT I:**

**Introduction:** Algorithm, Psuedo code for expressing algorithms, Performance Analysis-Space complexity, Time complexity, Asymptotic Notation- Big oh notation, Omega notation, Theta notation and Little oh notation, Probabilistic analysis, Amortized analysis.

**Searching and Traversal Techniques:** Efficient non - recursive binary tree traversal algorithm, Disjoint set operations, union and find algorithms, Spanning trees

### **UNIT II:**

**Divide and conquer:** General method , applications-Binary search, Quick sort, Merge sort, Strassen's matrix multiplication.

**Greedy method:** General method, applications - Job sequencing with deadlines, 0/1 knapsack problem, Minimum cost spanning trees, Single source shortest path problem.

### **UNIT III:**

**Dynamic Programming:** General method, applications-Matrix chain multiplication, Multi stage graphs, Optimal binary search trees, 0/1 knapsack problem, All pairs shortest path problem, Travelling sales person problem, Reliability design.

### **UNIT IV:**

**Graph traversals** - Breadth first search and Depth first search, AND / OR graphs, game trees, Connected Components, Bi - connected components.

**Backtracking:** General method, applications-n-queen problem, sum of subsets problem, graph coloring, Hamiltonian cycles.

### **UNIT V:**

**Branch and Bound:** General method, applications - Travelling sales person problem,0/1 knapsack problem- LC Branch and Bound solution, FIFO Branch and Bound solution.

**NP-Hard and NP-Complete problems:** Basic concepts, non deterministic algorithms, NP - Hard and NPComplete classes, Cook's theorem.

**TEXT BOOKS:**

1. Fundamentals of Computer Algorithms, Ellis Horowitz,Satraj Sahni and Rajasekharam,Galgotia publications pvt. Ltd.
2. Foundations of Algorithm, 4th edition, R. Neapolitan and K. Naimipour, Jones and Bartlett Learning.
3. Design and Analysis of Algorithms, P. H. Dave, H. B. Dave, Pearson Education, 2008.

**REFERENCES:**

1. Computer Algorithms, Introduction to Design and Analysis, 3rd Edition, Sara Baase, Allen, Van, Gelder, Pearson Education.
2. Algorithm Design: Foundations, Analysis and Internet examples, M. T. Goodrich and R. Tomassia, John Wiley and sons.
3. Fundamentals of Sequential and Parallel Algorithm, K. A. Berman and J. L. Paul, Cengage Learning.
4. Introduction to the Design and Analysis of Algorithms, A. Levitin, Pearson Education.
5. Introduction to Algorithms, 3rd Edition, T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, PHI Pvt. Ltd.
6. Design and Analysis of algorithm, Aho, Ullman and Hopcroft, Pearson Education, 2004.

**Outcomes:**

- Be able to analyze algorithms and improve the efficiency of algorithms.
- Apply different designing methods for development of algorithms to realistic problems, such as divide and conquer, greedy and etc. Ability to understand and estimate the performance of algorithm.

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**UNIT I:**

**Introduction:** Algorithm, Psuedo code for expressing algorithms, Performance Analysis-Space complexity, Time complexity, Asymptotic Notation- Big oh notation, Omega notation, Theta notation and Little oh notation, Probabilistic analysis, Amortized analysis.

**Searching and Traversal Techniques:** Efficient non - recursive binary tree traversal algorithm, Disjoint set operations, union and find algorithms, Spanning trees

**Algorithm:**

An Algorithm is a finite sequence of instructions, each of which has a clear meaning and can be performed with a finite amount of effort in a finite length of time. No matter what the input values may be, an algorithm terminates after executing a finite number of instructions. In addition every algorithm must satisfy the following criteria:

- **Input:** there are zero or more quantities, which are externally supplied;
- **Output:** at least one quantity is produced
- **Definiteness:** each instruction must be clear and unambiguous;
- **Finiteness:** if we trace out the instructions of an algorithm, then for all cases the algorithm will terminate after a finite number of steps;
- **Effectiveness:** every instruction must be sufficiently basic that it can in principle be carried out by a person using only pencil and paper. It is not enough that each operation be definite, but it must also be feasible.

In formal computer science, one distinguishes between an algorithm, and a program. A program does not necessarily satisfy the fourth condition. One important example of such a program for a computer is its operating system, which never terminates (except for system crashes) but continues in a wait loop until more jobs are entered.

We represent algorithm using a pseudo language that is a combination of the constructs of a programming language together with informal English statements.

**Pseudo code for expressing algorithms:**

**Algorithm Specification:** Algorithm can be described in three ways.

1. Natural language like English: When this way is chosen care should be taken, we should ensure that each & every statement is definite.
2. Graphic representation called flowchart: This method will work well when the algorithm is small& simple.
3. Pseudo-code Method: In this method, we should typically describe algorithms as programs, which resembles language like Pascal & algol.

**Pseudo-Code Conventions:**

1. Comments begin with // and continue until the end of line.
2. Blocks are indicated with matching braces {and}.
3. An identifier begins with a letter. The data types of variables are not explicitly declared.

4. Compound data types can be formed with records. Here is an example,

```
Node. Record
{
    data type - 1 data-1;
    .
    .
    .
    data type - n data - n;
    node * link;
}
```

Here link is a pointer to the record type node. Individual data items of a record can be accessed with → and period.

5. Assignment of values to variables is done using the assignment statement.

```
<Variable>:= <expression>;
```

6. There are two Boolean values TRUE and FALSE.

→ Logical Operators AND, OR, NOT  
→ Relational Operators <, <=,>,>=, =, !=

7. The following looping statements are employed.

For, while and repeat-until

**While Loop:**

```
While < condition > do
{
    <statement-1>
    .
    .
    .
}
```

```
<statement-n>
```

```
}
```

**For Loop:**

```
For variable: = value-1 to value-2 step step do
```

```
{  
<statement-1>  
..
```

```
<statement-n>
```

```
}
```

**repeat-until:**

```
repeat  
<statement-1>  
.  
.  
.
```

<statement-n>  
until<condition>

8. A conditional statement has the following forms.

- If <condition> then <statement>
- If <condition> then <statement-1>  
Else <statement-1>

**Case statement:**

```
Case
{
    : <condition-1> : <statement-1>
    .
    .
    .
    : <condition-n> : <statement-n>
    : else : <statement-n+1>
}
```

9. Input and output are done using the instructions read & write.

10. There is only one type of procedure:

Algorithm, the heading takes the form,

*Algorithm <Name> (<Parameter lists>)*

→ As an example, the following algorithm finds & returns the maximum of ‘n’ given numbers:

```
1. Algorithm Max(A,n)
2. // A is an array of size n
3. {
4. Result := A[1];
5. for I:= 2 to n do
6.     if A[I] > Result then
7.         Result :=A[I];
8.     return Result;
9. }
```

In this algorithm (named Max), A & n are procedure parameters. Result & I are Local variables.

**Algorithm:**

```
1. Algorithm selection sort (a,n)
2. // Sort the array a[1:n] into non-decreasing
order. 3.{ 
4.     for I:=1 to n do
5.     {
6.         j:=I;
7.         for k:=i+1 to n do
```

```

8.           if (a[k]<a[j])
9.           t:=a[I];
10.          a[I]:=a[j];
11.          a[j]:=t;
12.      }
13.  }

```

## **Performance Analysis:**

The performance of a program is the amount of computer memory and time needed to run a program. We use two approaches to determine the performance of a program. One is analytical, and the other experimental. In performance analysis we use analytical methods, while in performance measurement we conduct experiments.

## **Time Complexity:**

The time needed by an algorithm expressed as a function of the size of a problem is called the *time complexity* of the algorithm. The time complexity of a program is the amount of computer time it needs to run to completion.

The limiting behavior of the complexity as size increases is called the asymptotic time complexity. It is the asymptotic complexity of an algorithm, which ultimately determines the size of problems that can be solved by the algorithm.

## **The Running time of a program**

When solving a problem we are faced with a choice among algorithms. The basis for this can be any one of the following:

- i. We would like an algorithm that is easy to understand code and debug.
- ii. We would like an algorithm that makes efficient use of the computer's resources, especially, one that runs as fast as possible.

## **Measuring the running time of a program**

The running time of a program depends on factors such as:

1. The input to the program.
2. The quality of code generated by the compiler used to create the object program.
3. The nature and speed of the instructions on the machine used to execute the program,
4. The time complexity of the algorithm underlying the program.

<i>Statement</i>	<i>S/e</i>	<i>Frequency</i>	<i>Total</i>
1. Algorithm Sum(a,n)	0	-	0
2.{	0	-	0
3. S=0.0;	1	1	1
4. for I=1 to n do	1	n+1	n+1
5. s=s+a[I];	1	n	n
6. return s;	1	1	1
7. }	0	-	0

The total time will be  $2n+3$

## Space Complexity:

The space complexity of a program is the amount of memory it needs to run to completion. The space need by a program has the following components:

**Instruction space:** Instruction space is the space needed to store the compiled version of the program instructions.

**Data space:** Data space is the space needed to store all constant and variable values. Data space has two components:

- Space needed by constants and simple variables in program.
- Space needed by dynamically allocated objects such as arrays and class instances.

**Environment stack space:** The environment stack is used to save information needed to resume execution of partially completed functions.

**Instruction Space:** The amount of instructions space that is needed depends on factors such as:

- The compiler used to complete the program into machinecode.
- The compiler options in effect at the time of compilation
- The target computer.

The space requirement  $s(p)$  of any algorithm  $p$  may therefore be written as,

$$S(P) = c + S_p(\text{Instance characteristics})$$

Where 'c' is a constant.

### Example 2:

```
Algorithm sum(a,n)
{
    s=0.0;
    for I=1 to n do
        s= s+a[I];
    return s;
}
```

- The problem instances for this algorithm are characterized by  $n$ , the number of elements to be summed. The space needed by ' $n$ ' is one word, since it is of type integer.
- The space needed by ' $a$ ' is the space needed by variables of type array of floating point numbers.
- This is atleast ' $n$ ' words, since ' $a$ ' must be large enough to hold the ' $n$ ' elements to be summed.
- So, we obtain  $S_{sum}(n) \geq (n+1)$   
[  $n$  for  $a[]$ , one each for  $n, I$  &  $s$  ]

## Complexity of Algorithms

The complexity of an algorithm  $M$  is the function  $f(n)$  which gives the running time and/or storage space requirement of the algorithm in terms of the size ' $n$ ' of the input data. Mostly, the storage space required by an algorithm is simply a multiple of the data size ' $n$ '. Complexity shall refer to the running time of the algorithm.

The function  $f(n)$ , gives the running time of an algorithm, depends not only on the size ' $n$ ' of the input data but also on the particular data. The complexity function  $f(n)$  for certain cases are:

1. Best Case : The minimum possible value of  $f(n)$  is called the best case.
2. Average Case : The expected value of  $f(n)$ .
3. Worst Case : The maximum value of  $f(n)$  for any key possible input.

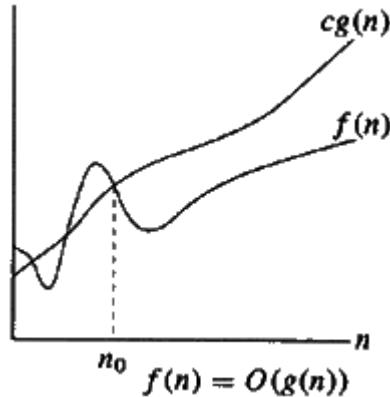
## Asymptotic Notations:

The following notations are commonly used notations in performance analysis and used to characterize the complexity of an algorithm:

1. Big-OH ( $O$ )
2. Big-OMEGA ( $\Omega$ ),
3. Big-THETA ( $\Theta$ ) and
4. Little-OH ( $o$ )

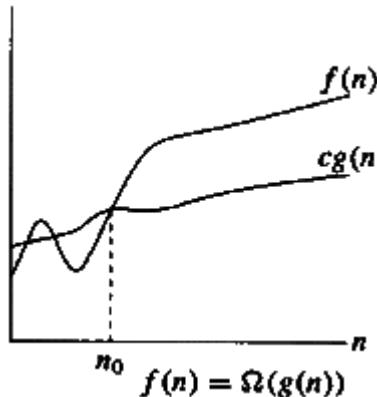
### **Big-OH $O$ (Upper Bound)**

$f(n) = O(g(n))$ , (pronounced order of or big oh), says that the growth rate of  $f(n)$  is less than or equal ( $\leq$ ) that of  $g(n)$ .



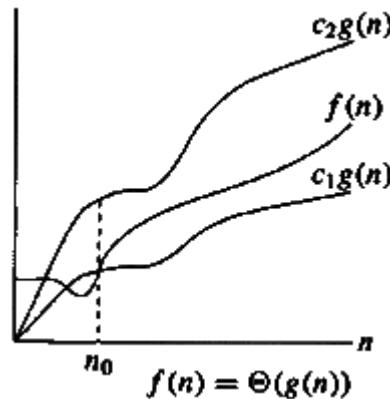
### **Big-OMEGA $\Omega$ (Lower Bound)**

$f(n) = \Omega(g(n))$  (pronounced omega), says that the growth rate of  $f(n)$  is greater than or equal to ( $\geq$ ) that of  $g(n)$ .



### **Big-THETA $\Theta$ (Same order)**

$f(n) = \Theta(g(n))$  (pronounced theta), says that the growth rate of  $f(n)$  equals (=) the growth rate of  $g(n)$  [if  $f(n) = O(g(n))$  and  $T(n) = \Theta(g(n))$ ].



### **little-o notation**

**Definition:** A theoretical measure of the execution of an *algorithm*, usually the time or memory needed, given the problem size  $n$ , which is usually the number of items. Informally, saying some equation  $f(n) = o(g(n))$  means  $f(n)$  becomes insignificant relative to  $g(n)$  as  $n$  approaches infinity. The notation is read, "f of n is little oh of g of n".

**Formal Definition:**  $f(n) = o(g(n))$  means for all  $c > 0$  there exists some  $k > 0$  such that  $0 \leq f(n) < cg(n)$  for all  $n \geq k$ . The value of  $k$  must not depend on  $n$ , but may depend on  $c$ .

### **Different time complexities**

Suppose 'M' is an algorithm, and suppose 'n' is the size of the input data. Clearly the complexity  $f(n)$  of M increases as  $n$  increases. It is usually the rate of increase of  $f(n)$  we want to examine. This is usually done by comparing  $f(n)$  with some standard functions. The most common computing times are:

$$O(1), O(\log_2 n), O(n), O(n \cdot \log_2 n), O(n^2), O(n^3), O(2^n), n! \text{ and } n^n$$

### **Classification of Algorithms**

If 'n' is the number of data items to be processed or degree of polynomial or the size of the file to be sorted or searched or the number of nodes in a graph etc.

- 1 Next instructions of most programs are executed once or at most only a few times. If all the instructions of a program have this property, we say that its running time is a constant.

**Log n** When the running time of a program is logarithmic, the program gets slightly slower as  $n$  grows. This running time commonly occurs in programs that solve a big problem by transforming it into a smaller problem, cutting the size by some constant fraction. When  $n$  is a million,  $\log n$  is doubled. Whenever  $n$  doubles,  $\log n$  increases by a constant, but  $\log n$  does not double until  $n$  increases to  $n^2$ .

**n** When the running time of a program is linear, it is generally the case that a small amount of processing is done on each input element. This is the optimal situation for an algorithm that must process  $n$  inputs.

- log n** This running time arises for algorithms that solve a problem by breaking it up into smaller sub-problems, solving them independently, and then combining the solutions. When  $n$  doubles, the running time more than doubles.

$n^2$

When the running time of an algorithm is quadratic, it is practical for use only on relatively small problems. Quadratic running times typically arise in algorithms that process all pairs of data items (perhaps in a double nested loop) whenever  $n$  doubles, the running time increases fourfold.

$n^3$

Similarly, an algorithm that processes triples of data items (perhaps in a triple-nested loop) has a cubic running time and is practical for use only on small problems. Whenever  $n$  doubles, the running time increases eight fold.

$2^n$

Few algorithms with exponential running time are likely to be appropriate for practical use, such algorithms arise naturally as “brute-force” solutions to problems. Whenever  $n$  doubles, the running time squares.

### Numerical Comparison of Different Algorithms

The execution time for six of the typical functions is given below:

<b>n</b>	<b>log2 n</b>	<b>n*log2n</b>	<b><math>n^2</math></b>	<b><math>n^3</math></b>	<b><math>2^n</math></b>
1	0	0	1	1	2
2	1	2	4	8	4
4	2	8	16	64	16
8	3	24	64	512	256
16	4	64	256	4096	65,536
32	5	160	1024	32,768	4,294,967,296
64	6	384	4096	2,62,144	Note 1
128	7	896	16,384	2,097,152	Note 2
256	8	2048	65,536	1,677,216	?????????

**Note1:** The value here is approximately the number of machine instructions executed by a 1 gigaflop computer in 5000 years.

### Probabilistic Analysis:

In analysis of algorithms, probabilistic analysis of algorithms is an approach to estimate the computational complexity of an algorithm or a computational problem. It starts from an assumption about a probabilistic distribution of the set of all possible inputs. This assumption is then used to design an efficient algorithm or to derive the complexity of known algorithms.

This approach is not the same as that of probabilistic algorithms, but the two may be combined.

For non-probabilistic, more specifically, for deterministic algorithms, the most common types of complexity estimates are the average-case complexity (expected time complexity)<sup>[dubious – discuss]</sup> and the almost always complexity. To obtain the average-case complexity, given an input distribution, the expected time of an algorithm is evaluated, whereas for the almost always complexity estimate, it is evaluated that the algorithm admits a given complexity estimate that almost surely holds.

In probabilistic analysis of probabilistic (randomized) algorithms, the distributions or averaging for all possible choices in randomized steps are also taken into account, in addition to the input distributions.

## Amortized Analysis:

**Amortized analysis** is a method of analyzing the costs associated with a data structure that averages the worst operations out over time. Often, a data structure has one particularly costly operation, but it doesn't get performed very often. That data structure shouldn't be labeled a costly structure just because that one operation, that is seldom performed, is costly.

So, amortized analysis is used to average out the costly operations in the worst case. The worst-case scenario for a data structure is the absolute worst ordering of operations from a cost perspective. Once that ordering is found, then the operations can be averaged.

There are three main types of amortized analysis: aggregate analysis, the accounting method, and the potential method.

In the **aggregate method** of amortized analysis, we show that for all  $n$ , a sequence of  $n$  operations takes *worst-case* time  $T(n)$  in total. In the worst case, the average cost, or **amortized cost**, per operation is therefore  $T(n) / n$ . Note that this amortized cost applies to each operation, even when there are several types of operations in the sequence.

In the **accounting method** of amortized analysis, we assign differing charges to different operations, with some operations charged more or less than they actually cost. The amount we charge an operation is called its **amortized cost**. When an operation's amortized cost exceeds its actual cost, the difference is assigned to specific objects in the data structure as **credit**. Credit can be used later on to help pay for operations whose amortized cost is less than their actual cost. Thus, one can view the amortized cost of an operation as being split between its actual cost and credit that is either deposited or used up. This is very different from the aggregate method, in which all operations have the same amortized cost.

Instead of representing prepaid work as credit stored with specific objects in the data structure, the **potential method** of amortized analysis represents the prepaid work as "potential energy," or just "potential," that can be released to pay for future operations. The potential is associated with the data structure as a whole rather than with specific objects within the data structure.

The potential method works as follows. We start with an initial data structure  $D_0$  on which  $n$  operations are performed. For each  $i = 1, 2, \dots, n$ , we let  $c_i$  be the actual cost of the  $i$ th operation and  $D_i$  be the data structure that results after applying the  $i$ th operation to data structure  $D_{i-1}$ . A **potential function**  $\Phi$  maps each data structure  $D_i$  to a real number  $\Phi(D_i)$ , which is the **potential** associated with data structure  $D_i$ . The **amortized cost**  $\hat{c}_i$  of the  $i$ th operation with respect to potential function  $\Phi$  is defined by

$$\hat{c}_i = c_i + \Phi(D_i) - \Phi(D_{i-1}) . \quad (18.1)$$

# Searching and Traversal Techniques

## Non Recursive Binary Tree Traversal Algorithms:

### Inorder Traversal:

Initially push zero onto stack and then set root as vertex. Then repeat the following steps until the stack is empty:

1. Proceed down the left most path rooted at vertex, pushing each vertex onto the stack and stop when there is no left son of vertex.
2. Pop and process the nodes on stack if zero is popped then exit. If a vertex with right son exists, then set right son of vertex as current vertex and return to step one.

The algorithm for inorder Non Recursive traversal is as follows:

```
Algorithm inorder()
{
    stack[1] = 0
    vertex = root
top: while(vertex != 0)
{
    push the vertex into the stack
    vertex = leftson(vertex)
}

pop the element from the stack and make it as vertex

while(vertex != 0)
{
    print the vertex node
    if(rightson(vertex) != 0)
    {
        vertex = rightson(vertex)
        goto top
    }
    pop the element from the stack and made it as vertex
}
}
```

### Preorder Traversal:

Initially push zero onto stack and then set root as vertex. Then repeat the following steps until the stack is empty:

1. Proceed down the left most path by pushing the right son of vertex onto stack, if any and process each vertex. The traversing ends after a vertex with no left child exists.
2. Pop the vertex from stack, if vertex  $\neq 0$  then return to step one otherwise exit.

The algorithm for preorder Non Recursive traversal is as follows:

```
Algorithm preorder( )
{
    stack[1] := 0
    vertex := root.
    while(vertex ≠ 0)
    {
        print vertex node
        if(rightson(vertex) ≠ 0)
            push the right son of vertex into the stack.
        if(leftson(vertex) ≠ 0)
            vertex := leftson(vertex)
        else
            pop the element from the stack and made it as vertex
    }
}
```

### **Postorder Traversal:**

Initially push zero onto stack and then set root as vertex. Then repeat the following steps until the stack is empty:

1. Proceed down the left most path rooted at vertex. At each vertex of path push vertex on to stack and if vertex has a right son push -(right son of vertex) onto stack.
2. Pop and process the positive nodes (left nodes). If zero is popped then exit. If a negative node is popped, then ignore the sign and return to step one.

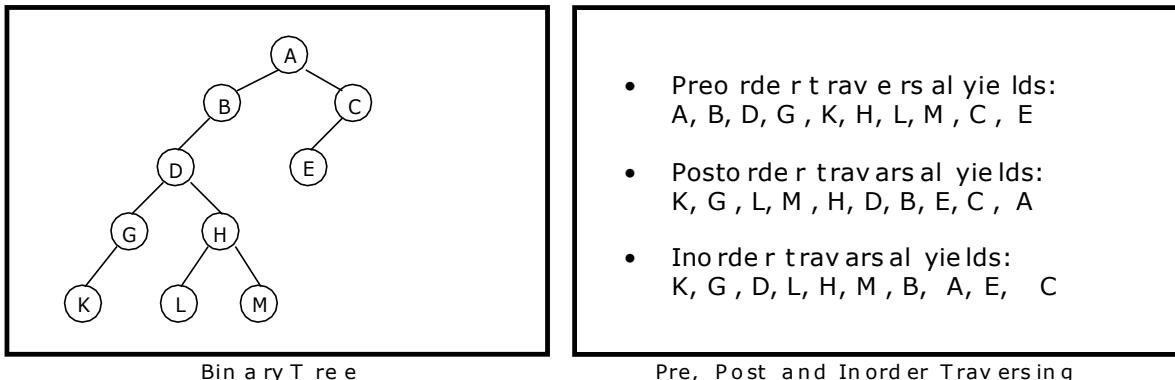
The algorithm for postorder Non Recursive traversal is as follows:

```
Algorithm postorder( )
{
    stack[1] := 0
    vertex := root

    top: while(vertex ≠ 0)
    {
        push vertex onto stack
        if(rightson(vertex) ≠ 0)
            push -(vertex) onto stack
        vertex := leftson(vertex)
    }
    pop from stack and make it as vertex
    while(vertex > 0)
    {
        print the vertex node
        pop from stack and make it as vertex
    }
    if(vertex < 0)
    {
        vertex := -(vertex)
        goto top
    }
}
```

### Example :

Traverse the following binary tree in pre, post and inorder using non-recursive traversing algorithm.



### Inorder Traversal:

Initially push zero onto stack and then set root as vertex. Then repeat the following steps until the stack is empty:

1. Proceed down the left most path rooted at vertex, pushing each vertex onto the stack and stop when there is no left son of vertex.
2. Pop and process the nodes on stack if zero is popped then exit. If a vertex with right son exists, then set right son of vertex as current vertex and return to step one.

Current vertex	Stack	Processed nodes	Remarks
A	0		PUSH 0
	0 A B D G K		PUSH the left most path of A
K	0 A B D G	K	POP K
G	0 A B D	K G	POP G since K has no right son
D	0 A B	K G D	POP D since G has no right son
H	0 A B	K G D	Make the right son of D as vertex
H	0 A B H L	K G D	PUSH the leftmost path of H
L	0 A B H	K G D L	POP L
H	0 A B	K G D L H	POP H since L has no right son
M	0 A B	K G D L H	Make the right son of H as vertex
	0 A B M	K G D L H	PUSH the left most path of M
M	0 A B	K G D L H M	POP M
B	0 A	K G D L H M B	POP B since M has no right son
A	0	K G D L H M B A	Make the right son of A as vertex
C	0 C E	K G D L H M B A	PUSH the left most path of C
E	0 C	K G D L H M B A E	POP E
C	0	K G D L H M B A E C	Stop since stack is empty

### **Postorder Traversal:**

Initially push zero onto stack and then set root as vertex. Then repeat the following steps until the stack is empty:

1. Proceed down the left most path rooted at vertex. At each vertex of path push vertex on to stack and if vertex has a right son push -(right son of vertex) onto stack.
2. Pop and process the positive nodes (left nodes). If zero is popped then exit. If a negative node is popped, then ignore the sign and return to step one.

<b>Current vertex</b>	<b>Stack</b>	<b>Processed nodes</b>	<b>Remarks</b>
A	0		PUSH 0
	0 A -C B D -H G K		PUSH the left most path of A with a -ve for right sons
	0 A -C B D -H	K G	POP all +ve nodes K and G
H	0 A -C B D	K G	Pop H
	0 A -C B D H -M L	K G	PUSH the left most path of H with a -ve for right sons
	0 A -C B D H -M	K G L	POP all +ve nodes L
M	0 A -C B D H	K G L	Pop M
	0 A -C B D H M	K G L	PUSH the left most path of M with a -ve for right sons
	0 A -C	K G L M H D B	POP all +ve nodes M, H, D and B
C	0 A	K G L M H D B	Pop C
	0 A C E	K G L M H D B	PUSH the left most path of C with a -ve for right sons
	0	K G L M H D B E C A	POP all +ve nodes E, C and A
	0		Stop since stack is empty

### Preorder Traversal:

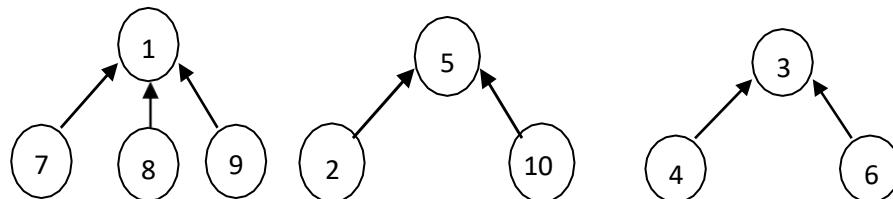
Initially push zero onto stack and then set root as vertex. Then repeat the following steps until the stack is empty:

1. Proceed down the left most path by pushing the right son of vertex onto stack, if any and process each vertex. The traversing ends after a vertex with no left child exists.
2. Pop the vertex from stack, if vertex  $\neq 0$  then return to step one otherwise exit.

Current vertex	Stack	Processed nodes	Remarks
A	0		PUSH 0
	0 C H	A B D G K	PUSH the right son of each vertex onto stack and process each vertex in the left most path
H	0 C	A B D G K	POP H
	0 C M	A B D G K H L	PUSH the right son of each vertex onto stack and process each vertex in the left most path
M	0 C	A B D G K H L	POP M
	0 C	A B D G K H L M	PUSH the right son of each vertex onto stack and process each vertex in the left most path; M has no left path
C	0	A B D G K H L M	Pop C
	0	A B D G K H L M C E	PUSH the right son of each vertex onto stack and process each vertex in the left most path; C has no right son on the left most path
	0	A B D G K H L M C E	Stop since stack is empty

### Sets and Disjoint Set Union:

Disjoint Set Union: Considering a set  $S=\{1,2,3\dots 10\}$  (when  $n=10$ ), then elements can be partitioned into three disjoint sets  $s_1=\{1,7,8,9\}$ ,  $s_2=\{2,5,10\}$  and  $s_3=\{3,4,6\}$ . Possible tree representations are:



In this representation each set is represented as a tree. Nodes are linked from the child to parent rather than usual method of linking from parent to child.

The operations on these sets are:

1. Disjoint set union
2. Find(i)
3. Min Operation
4. Delete
5. Intersect

### **1. Disjoint Set union:**

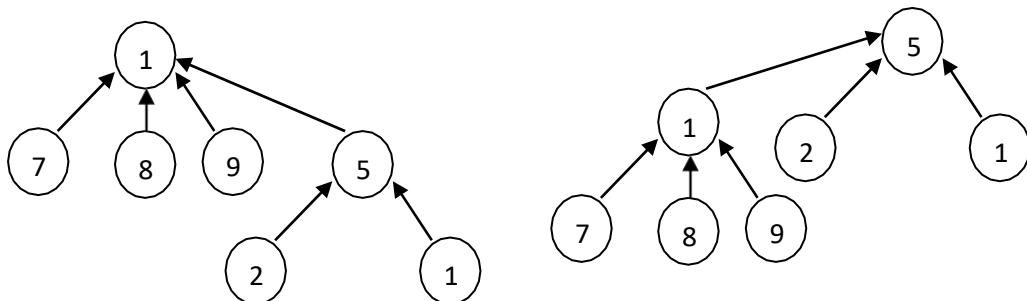
If  $S_i$  and  $S_j$  are two disjoint sets, then their union  $S_i \cup S_j =$  all the elements  $x$  such that  $x$  is in  $S_i$  or  $S_j$ . Thus  $S_1 \cup S_2 = \{1,7,8,9,2,5,10\}$ .

### **2. Find(i):**

Given the element  $i$ , find the set containing  $i$ . Thus, 4 is in set  $S_3$ , 9 is in  $S_1$ .

### **UNION operation:**

$\text{Union}(i,j)$  requires two tree with roots  $i$  and  $j$  be joined.  $S_1 \cup S_2$  is obtained by making any one of the sets as sub tree of other.



Simple Algorithm for Union:

```
Algorithm Union(i,j)
{
//replace the disjoint sets with roots i and j, I not equal to j by their
union Integer i,j;
P[j] :=i;
}
```

### **Example:**

Implement following sequence of operations  $\text{Union}(1,3), \text{Union}(2,5), \text{Union}(1,2)$

### **Solution:**

Initially parent array contains zeros.

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

1. After performing  
 $\text{union}(1,3)$  operation  
 $\text{Parent}[3]:=1$

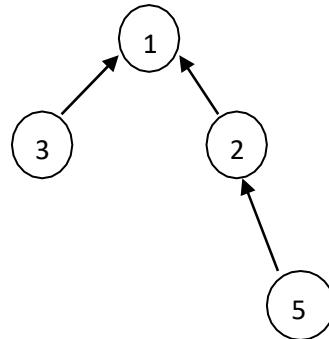
0	0	1	0	0	0
1	2	3	4	5	6

2. After performing  
 $\text{union}(2,5)$  operation  
 $\text{Parent}[5]:=2$

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

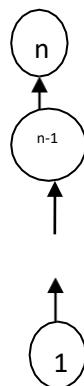
1. After performing  $\text{union}(1,2)$  operation  
 $\text{Parent}[2]:=1$

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



Process the following sequence of union operations Union(1,2),Union(2,3) Union(n-1,n)

### Degenerate Tree:



The time taken for  $n-1$  unions is  $O(n)$ .

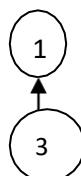
**Find(i) operation:** determines the root of the tree containing element i. Simple Algorithm for Find:

Algorithm Find(i)

```
{
    j:=i;
    while(p[j]>0) do
        j:=p[j];
    return j;
}
```

**Find Operation:** Find(i) implies that it finds the root node of  $i^{\text{th}}$  node, in other words it returns the name of the set i.

**Example:** Consider the Union(1,3)

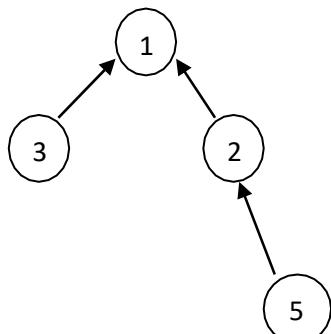


Find(1)=0

Find(3)=1, since its parent is 1. (i.e, root is 1)

**Example:**

Considering



Array Representation

P[i] ]	0	1	1	2
i	1	2	3	5

Find(5)=

1

Find(2)=

1

Find(3)=

1

The root node represents all the nodes in the tree. Time Complexity of 'n' find operations is  $O(n^2)$ .

To improve the performance of union and find algorithms by avoiding the creation of degenerate tree. To accomplish this, we use weighting rule for Union(i,j).

## Weighting Rule for Union(i,j)

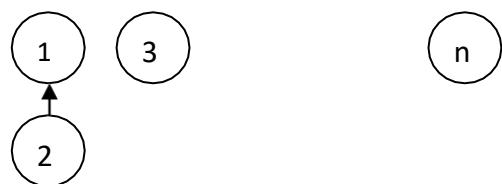
```
1  Algorithm WeightedUnion( $i, j$ )
2  // Union sets with roots  $i$  and  $j$ ,  $i \neq j$ , using the
3  // weighting rule.  $p[i] = -count[i]$  and  $p[j] = -count[j]$ .
4  {
5      temp :=  $p[i] + p[j]$ ;
6      if ( $p[i] > p[j]$ ) then
7          { //  $i$  has fewer nodes.
8               $p[i] := j$ ;  $p[j] := temp$ ;
9          }
10     else
11         { //  $j$  has fewer or equal nodes.
12              $p[j] := i$ ;  $p[i] := temp$ ;
13         }
14 }
```

Union algorithm with weighting rule

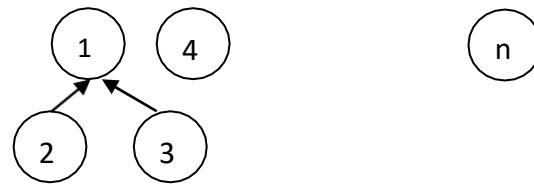
Tree obtained with  
weighted Initially



Union(1,2)

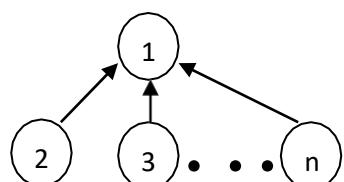


Union(1,3)



:  
:  
:

Union(1,n)



## Collapsing Rule for Find(i)

---

```
1  Algorithm CollapsingFind(i)
2    // Find the root of the tree containing element i. Use the
3    // collapsing rule to collapse all nodes from i to the root.
4    {
5      r := i;
6      while (p[r] > 0) do r := p[r]; // Find the root.
7      while (i ≠ r) do // Collapse nodes from i to root r.
8      {
9        s := p[i]; p[i] := r; i := s;
10     }
11   return r;
12 }
```

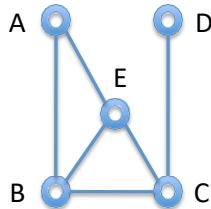
---

Find algorithm with collapsing rule

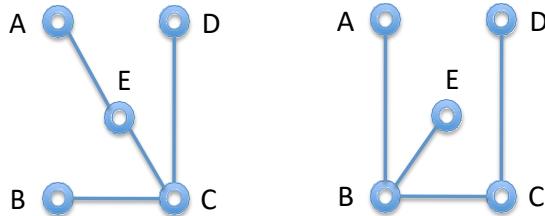
## Spanning Trees

We start with *undirected graphs* which consist of a set  $V$  of vertices (also called *nodes*) and a set  $E$  of edges, each connecting two different vertices. A graph is connected if we can reach any vertex from any other vertex by following edges in either direction. In a *directed graph* edges provide a connection from one node to another, but not necessarily in the opposite direction. More mathematically, we say that the edge relation between vertices is *symmetric* for undirected graphs. In this lecture we only discuss undirected graphs, although directed graphs also play an important role in many applications.

The following is a simple example of a connected, undirected graph with 5 vertices ( $A, B, C, D, E$ ) and 6 edges ( $AB, BC, CD, AE, BE, CE$ ).



In this lecture we are particularly interested in the problem of computing a *spanning tree* for a connected graph. What is a tree here? They are a bit different than the binary search trees we considered early. One simple definition is that a *tree* is a *connected graph with no cycles*, where a cycle lets you go from a node to itself without repeating an edge. A *spanning tree* for a connected graph  $G$  is a tree containing all the vertices of  $G$ . Below are two examples of spanning trees for our original example graph.



When dealing with a new kind of data structure, it is a good strategy to try to think of as many different characterization as we can. This is somewhat similar to the problem of coming up with good representations of the data; different ones may be appropriate for different purposes. Here are some alternative characterizations the class came up with:

1. Connected graph with no cycle (original).
2. Connected graph where no two neighbors are otherwise connected. *Neighbors* are vertices connected directly by an edge, *otherwise connected* means connected without the connecting edge.

**UNIT II:**

**Divide and conquer:** General method , applications-Binary search, Quick sort, Merge sort, Strassen's matrix multiplication.

**Greedy method:** General method, applications - Job sequencing with deadlines, 0/1 knapsack problem, Minimum cost spanning trees, Single source shortest path problem.

## Divide and Conquer

### General Method:

Divide and conquer is a design strategy which is well known to breaking down efficiency barriers. When the method applies, it often leads to a large improvement in time complexity. For example, from  $O(n^2)$  to  $O(n \log n)$  to sort the elements.

Divide and conquer strategy is as follows: divide the problem instance into two or more smaller instances of the same problem, solve the smaller instances recursively, and assemble the solutions to form a solution of the original instance. The recursion stops when an instance is reached which is too small to divide. When dividing the instance, one can either use whatever division comes most easily to hand or invest time in making the division carefully so that the assembly is simplified.

Divide and conquer algorithm consists of two parts:

- Divide : Divide the problem into a number of sub problems. The sub problems are solved recursively.  
Conquer : The solution to the original problem is then formed from the solutions to the sub problems (patching together the answers).

Traditionally, routines in which the text contains at least two recursive calls are called divide and conquer algorithms, while routines whose text contains only one recursive call are not. Divide-and-conquer is a very powerful use of recursion.

### Control Abstraction of Divide and Conquer

A control abstraction is a procedure whose flow of control is clear but whose primary operations are specified by other procedures whose precise meanings are left undefined. The control abstraction for divide and conquer technique is DANDC(P), where P is the problem to be solved.

```
DANDC (P)
{
    if SMALL (P) then return S (p);
    else
    {
        divide p into smaller instances p1, p2, ..., pk, k ≥ 1;
        apply DANDC to each of these sub problems;
        return (COMBINE (DANDC (p1) , DANDC (p2),..., DANDC (pk)));
    }
}
```

SMALL (P) is a Boolean valued function which determines whether the input size is small enough so that the answer can be computed without splitting. If this is so function 'S' is invoked otherwise, the problem 'p' into smaller sub problems. These sub problems p<sub>1</sub>, p<sub>2</sub>, . . . , p<sub>k</sub> are solved by recursive application of DANDC.

If the sizes of the two sub problems are approximately equal then the computing time of DANDC is:

$$T(n) = \begin{cases} g(n) & n \text{ small} \\ 2T(n/2) + f(n) & \text{otherwise} \end{cases}$$

Where,  $T(n)$  is the time for DANDC on ' $n$ ' inputs

$g(n)$  is the time to complete the answer directly for small inputs and

$f(n)$  is the time for Divide and Combine

## Binary Search:

If we have ' $n$ ' records which have been ordered by keys so that  $x_1 < x_2 < \dots < x_n$ . When we are given an element ' $x$ ', binary search is used to find the corresponding element from the list. In case ' $x$ ' is present, we have to determine a value ' $j$ ' such that  $a[j] = x$  (successful search). If ' $x$ ' is not in the list then  $j$  is to be set to zero (unsuccessful search).

In Binary search we jump into the middle of the file, where we find key  $a[mid]$ , and compare ' $x$ ' with  $a[mid]$ . If  $x = a[mid]$  then the desired record has been found. If  $x < a[mid]$  then ' $x$ ' must be in that portion of the file that precedes  $a[mid]$ , if there at all. Similarly, if  $a[mid] > x$ , then further search is only necessary in that part of the file which follows  $a[mid]$ . If we use recursive procedure of finding the middle key  $a[mid]$  of the un-searched portion of a file, then every un-successful comparison of ' $x$ ' with  $a[mid]$  will eliminate roughly half the un-searched portion from consideration.

Since the array size is roughly halved often each comparison between ' $x$ ' and  $a[mid]$ , and since an array of length ' $n$ ' can be halved only about  $\log_2 n$  times before reaching a trivial length, the worst case complexity of Binary search is about  **$\log_2 n$**

*low* and *high* are integer variables such that each time through the loop either ' $x$ ' is found or *low* is increased by at least one or *high* is decreased by at least one. Thus we have two sequences of integers approaching each other and eventually *low* will become greater than *high* causing termination in a finite number of steps if ' $x$ ' is not present.

---

```

1  Algorithm BinSrch( $a, i, l, x$ )
2  // Given an array  $a[i : l]$  of elements in nondecreasing
3  // order,  $1 \leq i \leq l$ , determine whether  $x$  is present, and
4  // if so, return  $j$  such that  $x = a[j]$ ; else return 0.
5  {
6      if ( $l = i$ ) then // If Small( $P$ )
7      {
8          if ( $x = a[i]$ ) then return  $i$ ;
9          else return 0;
10     }
11     else
12     { // Reduce  $P$  into a smaller subproblem.
13          $mid := \lfloor (i + l)/2 \rfloor$ ;
14         if ( $x = a[mid]$ ) then return  $mid$ ;
15         else if ( $x < a[mid]$ ) then
16             return BinSrch( $a, i, mid - 1, x$ );
17         else return BinSrch( $a, mid + 1, l, x$ );
18     }
19 }
```

---

Recursive binary search

---

```

1  Algorithm BinSearch( $a, n, x$ )
2  // Given an array  $a[1 : n]$  of elements in nondecreasing
3  // order,  $n \geq 0$ , determine whether  $x$  is present, and
4  // if so, return  $j$  such that  $x = a[j]$ ; else return 0.
5  {
6       $low := 1$ ;  $high := n$ ;
7      while ( $low \leq high$ ) do
8      {
9           $mid := \lfloor (low + high)/2 \rfloor$ ;
10         if ( $x < a[mid]$ ) then  $high := mid - 1$ ;
11         else if ( $x > a[mid]$ ) then  $low := mid + 1$ ;
12         else return  $mid$ ;
13     }
14     return 0;
15 }
```

---

Iterative binary search

### Example for Binary Search

Let us illustrate binary search on the following 9 elements:

Index	1	2	3	4	5	6	7	8	9
Elements	-15	-6	0	7	9	23	54	82	101

The number of comparisons required for searching different elements is as follows:

1. Searching for  $x = 101$

low	high	mid
1	9	5
6	9	7
8	9	8
9	9	9
found		

Number of comparisons = 4

2. Searching for  $x = 82$

low	high	mid
1	9	5
6	9	7
8	9	8
found		

Number of comparisons = 3

3. Searching for  $x = 42$

low	high	mid
1	9	5
6	9	7
6	6	6
7	6	not found

Number of comparisons = 4

4. Searching for  $x = -14$

low	high	mid
1	9	5
1	4	2
1	1	1
2	1	not found

Number of comparisons = 3

Continuing in this manner the number of element comparisons needed to find each of nine elements is:

Index	1	2	3	4	5	6	7	8	9
Elements	-15	-6	0	7	9	23	54	82	101
Comparisons	3	2	3	4	1	3	2	3	4

No element requires more than 4 comparisons to be found. Summing the comparisons needed to find all nine items and dividing by 9, yielding  $25/9$  or approximately 2.77 comparisons per successful search on the average.

There are ten possible ways that an un-successful search may terminate depending upon the value of  $x$ .

If  $x < a[1]$ ,  $a[1] < x < a[2]$ ,  $a[2] < x < a[3]$ ,  $a[5] < x < a[6]$ ,  $a[6] < x < a[7]$  or  $a[7] < x < a[8]$  the algorithm requires 3 element comparisons to determine that 'x' is not present. For all of the remaining possibilities BINSRCH requires 4 element comparisons. Thus the average number of element comparisons for an unsuccessful search is:

$$(3 + 3 + 3 + 4 + 4 + 3 + 3 + 3 + 4 + 4) / 10 = 34/10 = 3.4$$

The time complexity for a successful search is  $O(\log n)$  and for an unsuccessful search is  $\Theta(\log n)$ .

<b>Successful searches</b>			<b>un-successful searches</b>
$\Theta(1)$ , Best	$\Theta(\log n)$ , average	$\Theta(\log n)$ , worst	$\Theta(\log n)$ , best, average and worst

### Analysis for worst case

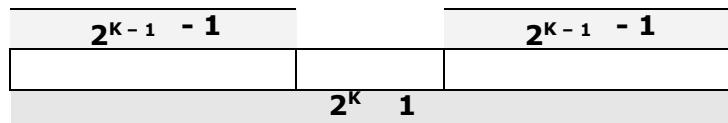
Let  $T(n)$  be the time complexity of Binary search

The algorithm sets mid to  $[n+1 / 2]$

Therefore,

$$\begin{aligned} T(0) &= 0 \\ T(n) &= 1 && \text{if } x = a[\text{mid}] \\ &= 1 + T([(n+1)/2] - 1) && \text{if } x < a[\text{mid}] \\ &= 1 + T(n - [(n+1)/2]) && \text{if } x > a[\text{mid}] \end{aligned}$$

Let us restrict 'n' to values of the form  $n = 2^k - 1$ , where 'k' is a non-negative integer. The array always breaks symmetrically into two equal pieces plus middle element.



$$\text{Algebraically this is } \left\lceil \frac{n+1}{2} \right\rceil = \left\lceil \frac{2^k - 1 + 1}{2} \right\rceil = 2^{k-1} \quad \text{for } k > 1$$

Giving,

$$\begin{aligned} T(0) &= 0 \\ T(2^k - 1) &= 1 && \text{if } x = a[\text{mid}] \\ &= 1 + T(2^{k-1} - 1) && \text{if } x < a[\text{mid}] \\ &= 1 + T(2^{k-1} - 1) && \text{if } x > a[\text{mid}] \end{aligned}$$

In the worst case the test  $x = a[\text{mid}]$  always fails, so

$$w(0) = 0$$

$$w(2^k - 1) = 1 + w(2^{k-1} - 1)$$

This is now solved by repeated substitution:

$$w(2^k - 1) = 1 + w(2^{k-1} - 1)$$

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

For  $i \leq k$ , letting  $i = k$  gives  $w(2^k - 1) = K + w(0) = k$

But as  $2^K - 1 = n$ , so  $K = \log_2(n + 1)$ , so

$$w(n) = \log_2(n + 1) = O(\log n)$$

for  $n = 2^K - 1$ , concludes this analysis of binary search.

Although it might seem that the restriction of values of 'n' of the form  $2^K - 1$  weakens the result. In practice this does not matter very much,  $w(n)$  is a monotonic increasing function of 'n', and hence the formula given is a good approximation even when 'n' is not of the form  $2^K - 1$ .

## Merge Sort:

Merge sort algorithm is a classic example of divide and conquer. To sort an array, recursively, sort its left and right halves separately and then merge them. The time complexity of merge sort in the *best case*, *worst case* and *average case* is  $O(n \log n)$  and the number of comparisons used is nearly optimal.

This strategy is so simple, and so efficient but the problem here is that there seems to be no easy way to merge two adjacent sorted arrays together in place (The result must be built up in a separate array).

The fundamental operation in this algorithm is merging two sorted lists. Because the lists are sorted, this can be done in one pass through the input, if the output is put in a third list.

### Algorithm

#### **Algorithm MERGESORT (low, high)**

// a (low : high) is a global array to be sorted.

```

{
    if (low < high)
    {
        mid := |(low + high)/2|;           //finds where to split the set
        MERGESORT(low, mid);             //sort one subset
        MERGESORT(mid+1, high);         //sort the other subset
        MERGE(low, mid, high);          // combine the results
    }
}

```

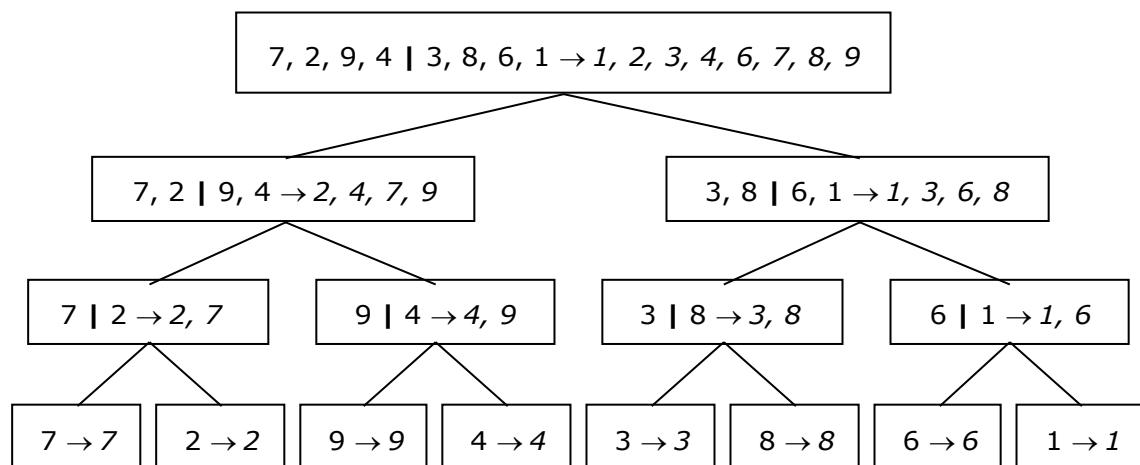
```

Algorithm MERGE (low, mid, high)
// a (low : high) is a global array containing two sorted subsets
// in a (low : mid) and in a (mid + 1 : high).
// The objective is to merge these sorted sets into single sorted
// set residing in a (low : high). An auxiliary array B is used.
{
    h := low; i := low; j := mid + 1;
    while ((h ≤ mid) and (j ≤ high)) do
    {
        if (a[h] ≤ a[j]) then
        {
            b[i] := a[h]; h := h + 1;
        }
        else
        {
            b[i] := a[j]; j := j + 1;
        }
        i := i + 1;
    }
    if (h > mid) then
        for k := j to high do
        {
            b[i] := a[k]; i := i + 1;
        }
    else
        for k := h to mid do
        {
            b[i] := a[k]; i := i + 1;
        }
    for k := low to high do
        a[k] := b[k];
}

```

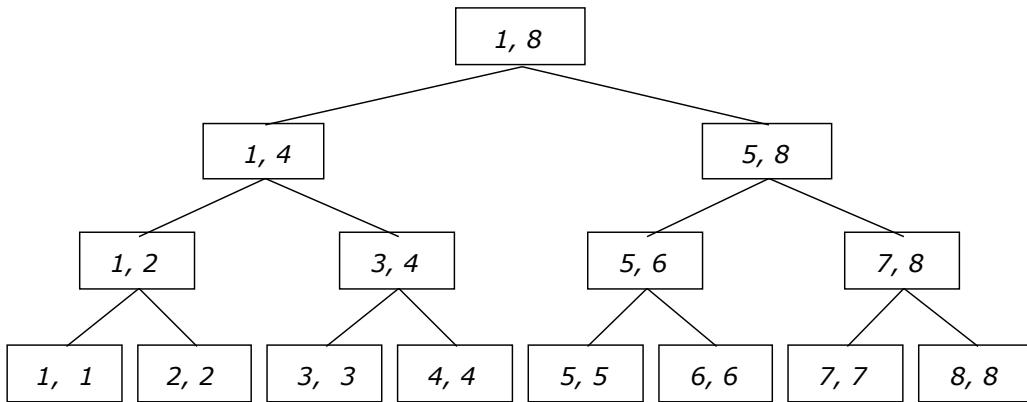
### Example

For example let us select the following 8 entries 7, 2, 9, 4, 3, 8, 6, 1 to illustrate merge sort algorithm:



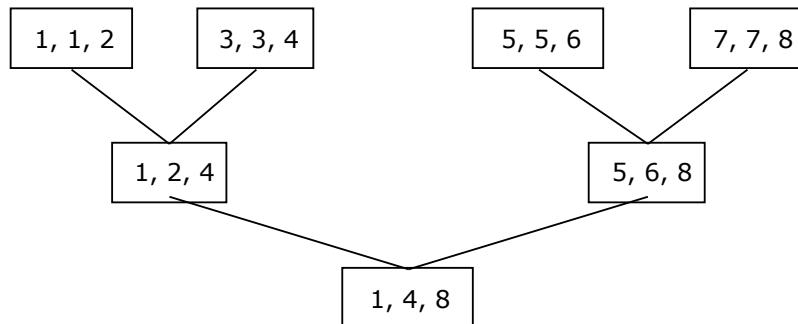
### Tree Calls of MERGESORT(1, 8)

The following figure represents the sequence of recursive calls that are produced by MERGESORT when it is applied to 8 elements. The values in each node are the values of the parameters low and high.



### Tree Calls of MERGE()

The tree representation of the calls to procedure MERGE by MERGESORT is as follows:



### Analysis of Merge Sort

We will assume that 'n' is a power of 2, so that we always split into even halves, so we solve for the case  $n = 2^k$ .

For  $n = 1$ , the time to merge sort is constant, which we will denote by 1. Otherwise, the time to merge sort 'n' numbers is equal to the time to do two recursive merge sorts of size  $n/2$ , plus the time to merge, which is linear. The equation says this exactly:

$$\begin{aligned} T(1) &= 1 \\ T(n) &= 2 T(n/2) + n \end{aligned}$$

This is a standard recurrence relation, which can be solved several ways. We will solve by substituting recurrence relation continually on the right-hand side.

We have,  $T(n) = 2T(n/2) + n$

Since we can substitute  $n/2$  into this main equation

$$\begin{aligned} 2 T(n/2) &= 2 (2 (T(n/4)) + n/2) \\ &= 4 T(n/4) + n \end{aligned}$$

We have,

$$\begin{aligned} T(n/2) &= 2 T(n/4) + n \\ T(n) &= 4 T(n/4) + 2n \end{aligned}$$

Again, by substituting  $n/4$  into the main equation, we see that

$$\begin{aligned} 4 T(n/4) &= 4 (2 T(n/8)) + n/4 \\ &= 8 T(n/8) + n \end{aligned}$$

So we have,

$$\begin{aligned} T(n/4) &= 2 T(n/8) + n \\ T(n) &= 8 T(n/8) + 3n \end{aligned}$$

Continuing in this manner, we obtain:

$$T(n) = 2^k T(n/2^k) + K \cdot n$$

As  $n = 2^k$ ,  $K = \log_2 n$ , substituting this in the above equation

$$\begin{aligned} T(n) &= 2^{\log_2 n} \left( \frac{2^k}{2} \right)^{\log_2 n} \cdot n \\ &= n T(1) + n \log n \\ &= n \log n + n \end{aligned}$$

Representing this in O notation:

$$T(n) = \mathbf{O}(n \log n)$$

We have assumed that  $n = 2^k$ . The analysis can be refined to handle cases when 'n' is not a power of 2. The answer turns out to be almost identical.

Although merge sort's running time is  $O(n \log n)$ , it is hardly ever used for main memory sorts. The main problem is that merging two sorted lists requires linear extra memory and the additional work spent copying to the temporary array and back, throughout the algorithm, has the effect of slowing down the sort considerably. *The Best and worst case time complexity of Merge sort is  $O(n \log n)$ .*

### **Strassen's Matrix Multiplication:**

The matrix multiplication of algorithm due to Strassens is the most dramatic example of divide and conquer technique (1969).

The usual way to multiply two  $n \times n$  matrices A and B, yielding result matrix 'C' as follows :

```
for i := 1 to n do
    for j := 1 to n do
        c[i, j] := 0;
        for K := 1 to n do
            c[i, j] := c[i, j] + a[i, k] * b[k, j];
```

This algorithm requires  $n^3$  scalar multiplication's (i.e. multiplication of single numbers) and  $n^3$  scalar additions. So we naturally cannot improve upon.

We apply divide and conquer to this problem. For example let us consider three multiplication like this:

$$\begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix}$$

Then  $C_{ij}$  can be found by the usual matrix multiplication algorithm,

$$C_{11} = A_{11} \cdot B_{11} + A_{12} \cdot B_{21}$$

$$C_{12} = A_{11} \cdot B_{12} + A_{12} \cdot B_{22}$$

$$C_{21} = A_{21} \cdot B_{11} + A_{22} \cdot B_{21}$$

$$C_{22} = A_{21} \cdot B_{12} + A_{22} \cdot B_{22}$$

This leads to a divide-and-conquer algorithm, which performs  $n \times n$  matrix multiplication by partitioning the matrices into quarters and performing eight  $(n/2) \times (n/2)$  matrix multiplications and four  $(n/2) \times (n/2)$  matrix additions.

$$\begin{aligned} T(1) &= 1 \\ T(n) &= 8 T(n/2) \end{aligned}$$

Which leads to  $T(n) = O(n^3)$ , where  $n$  is the power of 2.

Strassens insight was to find an alternative method for calculating the  $C_{ij}$ , requiring seven  $(n/2) \times (n/2)$  matrix multiplications and eighteen  $(n/2) \times (n/2)$  matrix additions and subtractions:

$$P = (A_{11} + A_{22}) (B_{11} + B_{22})$$

$$Q = (A_{21} + A_{22}) B_{11}$$

$$R = A_{11} (B_{12} - B_{22})$$

$$S = A_{22} (B_{21} - B_{11})$$

$$T = (A_{11} + A_{12}) B_{22}$$

$$U = (A_{21} - A_{11}) (B_{11} + B_{12})$$

$$V = (A_{12} - A_{22}) (B_{21} + B_{22})$$

$$C_{11} = P + S - T + V$$

$$C_{12} = R + T$$

$$C_{21} = Q + S$$

$$C_{22} = P + R - Q + U.$$

This method is used recursively to perform the seven  $(n/2) \times (n/2)$  matrix multiplications, then the recurrence equation for the number of scalar multiplications performed is:

$$\begin{aligned} T(1) &= 1 \\ T(n) &= 7 T(n/2) \end{aligned}$$

Solving this for the case of  $n = 2^k$  is easy:

$$\begin{aligned} T(2^k) &= 7 T(2^{k-1}) \\ &= 7^2 T(2^{k-2}) \\ &= \dots \\ &= \dots \\ &= 7^i T(2^{k-i}) \end{aligned}$$

Put  $i = k$

$$\begin{aligned} &= 7^k T(1) \\ &= 7^k \end{aligned}$$

That is,  $T(n) = 7^{\log_2 n}$

$$\begin{aligned} &= n^{\log_2 7} \\ &= O(n^{\log_2 7}) = O(2^{n^{\log_2 7}}) \end{aligned}$$

So, concluding that Strassen's algorithm is asymptotically more efficient than the standard algorithm. In practice, the overhead of managing the many small matrices does not pay off until 'n' revolves the hundreds.

## Quick Sort

The main reason for the slowness of Algorithms like SIS is that all comparisons and exchanges between keys in a sequence  $w_1, w_2, \dots, w_n$  take place between adjacent pairs. In this way it takes a relatively long time for a key that is badly out of place to work its way into its proper position in the sorted sequence.

Hoare devised a very efficient way of implementing this idea in the early 1960's that improves the  $O(n^2)$  behavior of SIS algorithm with an expected performance that is  $O(n \log n)$ .

In essence, the quick sort algorithm partitions the original array by rearranging it into two groups. The first group contains those elements less than some arbitrary chosen value taken from the set, and the second group contains those elements greater than or equal to the chosen value.

The chosen value is known as the *pivot element*. Once the array has been rearranged in this way with respect to the pivot, the very same partitioning is recursively applied to each of the two subsets. When all the subsets have been partitioned and rearranged, the original array is sorted.

The function `partition()` makes use of two pointers 'i' and 'j' which are moved toward each other in the following fashion:

- Repeatedly increase the pointer 'i' until  $a[i] \geq \text{pivot}$ .
- Repeatedly decrease the pointer 'j' until  $a[j] \leq \text{pivot}$ .

- If  $j > i$ , interchange  $a[j]$  with  $a[i]$
- Repeat the steps 1, 2 and 3 till the 'i' pointer crosses the 'j' pointer. If 'i' pointer crosses 'j' pointer, the position for pivot is found and place pivot element in 'j' pointer position.

The program uses a recursive function quicksort(). The algorithm of quick sort function sorts all elements in an array 'a' between positions 'low' and 'high'.

- It terminates when the condition  $low \geq high$  is satisfied. This condition will be satisfied only when the array is completely sorted.
- Here we choose the first element as the 'pivot'. So,  $pivot = x[low]$ . Now it calls the partition function to find the proper position  $j$  of the element  $x[low]$  i.e. pivot. Then we will have two sub-arrays  $x[low], x[low+1], \dots, \dots, x[j-1]$  and  $x[j+1], x[j+2], \dots, x[high]$ .
- It calls itself recursively to sort the left sub-array  $x[low], x[low+1], \dots, \dots, x[j-1]$  between positions low and  $j-1$  (where  $j$  is returned by the partition function).
- It calls itself recursively to sort the right sub-array  $x[j+1], x[j+2], \dots, \dots, x[high]$  between positions  $j+1$  and high.

```

1  Algorithm QuickSort( $p, q$ )
2  // Sorts the elements  $a[p], \dots, a[q]$  which reside in the global
3  // array  $a[1 : n]$  into ascending order;  $a[n + 1]$  is considered to
4  // be defined and must be  $\geq$  all the elements in  $a[1 : n]$ .
5  {
6      if ( $p < q$ ) then // If there are more than one element
7          {
8              // divide  $P$  into two subproblems.
9               $j := \text{Partition}(a, p, q + 1);$ 
10             //  $j$  is the position of the partitioning element.
11             // Solve the subproblems.
12             QuickSort( $p, j - 1$ );
13             QuickSort( $j + 1, q$ );
14             // There is no need for combining solutions.
15         }
16     }

```

---

```

1   Algorithm Partition( $a, m, p$ )
2   // Within  $a[m], a[m + 1], \dots, a[p - 1]$  the elements are
3   // rearranged in such a manner that if initially  $t = a[m]$ ,
4   // then after completion  $a[q] = t$  for some  $q$  between  $m$ 
5   // and  $p - 1$ ,  $a[k] \leq t$  for  $m \leq k < q$ , and  $a[k] \geq t$ 
6   // for  $q < k < p$ .  $q$  is returned. Set  $a[p] = \infty$ .
7   {
8        $v := a[m]; i := m; j := p;$ 
9       repeat
10      {
11          repeat
12               $i := i + 1;$ 
13          until ( $a[i] \geq v$ );
14          repeat
15               $j := j - 1;$ 
16          until ( $a[j] \leq v$ );
17          if ( $i < j$ ) then Interchange( $a, i, j$ );
18      } until ( $i \geq j$ );
19       $a[m] := a[j]; a[j] := v;$  return  $j$ ;
20  }

```

```

1   Algorithm Interchange( $a, i, j$ )
2   // Exchange  $a[i]$  with  $a[j]$ .
3   {
4        $p := a[i];$ 
5        $a[i] := a[j]; a[j] := p;$ 
6   }

```

---

### Example

Select first element as the pivot element. Move 'i' pointer from left to right in search of an element larger than pivot. Move the 'j' pointer from right to left in search of an element smaller than pivot. If such elements are found, the elements are swapped. This process continues till the 'i' pointer crosses the 'j' pointer. If 'i' pointer crosses 'j' pointer, the position for pivot is found and interchange pivot and element at 'j' position.

Let us consider the following example with 13 elements to analyze quick sort:

1	2	3	4	5	6	7	8	9	10	11	12	13	Remarks
38	08	16	06	79	57	24	56	02	58	04	70	45	
pivot				i						j			swap i & j
				04						79			
					i			j					swap i & j

					02			57					
						j	i						
(24	08	16	06	04	02)	<b>38</b>	(56	57	58	79	70	45)	swap pivot & j
pivot						j, i							swap pivot & j
(02	08	16	06	04)	<b>24</b>								
pivot, j	i												swap pivot & j
<b>02</b>	(08	16	06	04)									
pivot	i		j										swap i & j
	04		16										
		j	i										
(06	04)	<b>08</b>	(16)										swap pivot & j
pivot, j	i												
(04)	<b>06</b>												swap pivot & j
<b>04</b>	pivot, j, i												
				<b>16</b> pivot, j, i									
<b>(02</b>	<b>04</b>	<b>06</b>	<b>08</b>	<b>16</b>	<b>24)</b>	38							
							(56	57	58	79	70	45)	
						pivot	i					j	swap i & j
							45					57	
							j	i					
						(45)	<b>56</b>	(58	79	70	57)	swap pivot & j	
						<b>45</b> pivot, j, i							swap pivot & j
							(58	pivot	79	i	70	<b>57)</b>	swap i & j
									57			79	
								j	i				
							(57)	<b>58</b>	(70	79)	swap pivot & j		
								<b>57</b> pivot, j, i					
									(70	79)			
								pivot,	i	swap pivot & j			
									<b>70</b>				
										<b>79</b> pivot, j, i			
							(45	<b>56</b>	<b>57</b>	<b>58</b>	<b>70</b>	<b>79)</b>	
<b>02</b>	<b>04</b>	<b>06</b>	<b>08</b>	<b>16</b>	<b>24</b>	<b>38</b>	<b>45</b>	<b>56</b>	<b>57</b>	<b>58</b>	<b>70</b>	<b>79</b>	

## **Analysis of Quick Sort:**

Like merge sort, quick sort is recursive, and hence its analysis requires solving a recurrence formula. We will do the analysis for a quick sort, assuming a random pivot (and no cut off for small files).

We will take  $T(0) = T(1) = 1$ , as in merge sort.

The running time of quick sort is equal to the running time of the two recursive calls plus the linear time spent in the partition (The pivot selection takes only constant time). This gives the basic quick sort relation:

$$T(n) = T(i) + T(n - i - 1) + Cn \quad - \quad (1)$$

Where,  $i = |S_1|$  is the number of elements in  $S_1$ .

## **Worst Case Analysis**

The pivot is the smallest element, all the time. Then  $i=0$  and if we ignore  $T(0)=1$ , which is insignificant, the recurrence is:

$$T(n) = T(n - 1) + Cn \quad n > 1 \quad - \quad (2)$$

Using equation – (1) repeatedly, thus

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

$$T(n - 2) = T(n - 3) + C(n - 2)$$

- - - - -

$$T(2) = T(1) + C(2)$$

Adding up all these equations yields

$$\begin{aligned} T(n) &= T(1) + \sum_{i=2}^n i \\ &= O(n^2) \end{aligned} \quad - \quad (3)$$

## Best and Average Case Analysis

The number of comparisons for first call on partition: Assume left\_to\_right moves over k smaller element and thus k comparisons. So when right\_to\_left crosses left\_to\_right it has made  $n-k+1$  comparisons. So, first call on partition makes  $n+1$  comparisons. The average case complexity of quicksort is

$T(n)$  = comparisons for first call on quicksort

+

$$\{\sum_{1 \leq nleft, nright \leq n} [T(nleft) + T(nright)]\}n = (n+1) + 2[T(0) + T(1) + T(2) + \dots + T(n-1)]/n$$

$$nT(n) = n(n+1) + 2[T(0) + T(1) + T(2) + \dots + T(n-2) + T(n-1)]$$

$$(n-1)T(n-1) = (n-1)n + 2[T(0) + T(1) + T(2) + \dots + T(n-2)] \backslash$$

Subtracting both sides:

$$nT(n) - (n-1)T(n-1) = [n(n+1) - (n-1)n] + 2T(n-1) = 2n + 2T(n-1)$$

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

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

The recurrence relation obtained is:

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

Using the method of substitution:

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

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

$$T(n-2)/(n-1) = 2/(n-1) + T(n-3)/(n-2)$$

$$T(n-3)/(n-2) = 2/(n-2) + T(n-4)/(n-3)$$

.

.

$$T(3)/4 = 2/4 + T(2)/3$$

$$T(2)/3 = 2/3 + T(1)/2 \quad T(1)/2 = 2/2 + T(0)$$

Adding both sides:

$$T(n)/(n+1) + [T(n-1)/n + T(n-2)/(n-1) + \dots + T(2)/3 + T(1)/2]$$

$$= [T(n-1)/n + T(n-2)/(n-1) + \dots + T(2)/3 + T(1)/2] + T(0) +$$

$$[2/(n+1) + 2/n + 2/(n-1) + \dots + 2/4 + 2/3]$$

Cancelling the common terms:

$$T(n)/(n+1) = 2[1/2 + 1/3 + 1/4 + \dots + 1/n+1/(n+1)]$$

$$T(n) = (n+1)2 \left[ \sum_{2 \leq k \leq n+1} 1/k \right]$$

$$= 2(n+1) [ \dots - ]$$

$$= 2(n+1)[\log(n+1) - \log 2]$$

$$= 2n \log(n+1) + \log(n+1) - 2n \log 2 - \log 2$$

$$\mathbf{T(n)=O(n \log n)}$$

# Greedy Method

## GENERAL METHOD

Greedy is the most straight forward design technique. Most of the problems have n inputs and require us to obtain a subset that satisfies some constraints. Any subset that satisfies these constraints is called a feasible solution. We need to find a feasible solution that either maximizes or minimizes the objective function. A feasible solution that does this is called an optimal solution.

The greedy method is a simple strategy of progressively building up a solution, one element at a time, by choosing the best possible element at each stage. At each stage, a decision is made regarding whether or not a particular input is in an optimal solution. This is done by considering the inputs in an order determined by some selection procedure. If the inclusion of the next input, into the partially constructed optimal solution will result in an infeasible solution then this input is not added to the partial solution. The selection procedure itself is based on some optimization measure. Several optimization measures are plausible for a given problem. Most of them, however, will result in algorithms that generate sub-optimal solutions. This version of greedy technique is called *subset paradigm*. Some problems like Knapsack, Job sequencing with deadlines and minimum cost spanning trees are based on *subset paradigm*.

For the problems that make decisions by considering the inputs in some order, each decision is made using an optimization criterion that can be computed using decisions already made. This version of greedy method is *ordering paradigm*. Some problems like optimal storage on tapes, optimal merge patterns and single source shortest path are based on *ordering paradigm*.

## CONTROL ABSTRACTION

### Algorithm Greedy (a, n)

```
// a(1 : n) contains the 'n' inputs
{
    solution :=  $\emptyset$ ;           // initialize the solution to empty
    for i:=1 to n do
    {
        x := select (a);
        if feasible (solution, x) then
            solution := Union (Solution, x);
    }
    return solution;
}
```

Procedure Greedy describes the essential way that a greedy based algorithm will look, once a particular problem is chosen and the functions select, feasible and union are properly implemented.

The function select selects an input from 'a', removes it and assigns its value to 'x'. Feasible is a Boolean valued function, which determines if 'x' can be included into the solution vector. The function Union combines 'x' with solution and updates the objective function.

## **KNAPSACK PROBLEM:**

Let us apply the greedy method to solve the knapsack problem. We are given 'n' objects and a knapsack. The object 'i' has a weight  $w_i$  and the knapsack has a capacity 'm'. If a fraction  $x_i$ ,  $0 < x_i < 1$  of object i is placed into the knapsack then a profit of  $p_i x_i$  is earned. The objective is to fill the knapsack that maximizes the total profit earned.

Since the knapsack capacity is 'm', we require the total weight of all chosen objects to be at most 'm'. The problem is stated as:

$$\begin{aligned} \text{maximize } & \sum_{i=1}^n p_i x_i \\ \text{subject to } & \sum_{i=1}^n a_i x_i \leq M \quad \text{where, } 0 \leq x_i \leq 1 \text{ and } 1 \leq i \leq n \end{aligned}$$

The profits and weights are positive numbers.

If the objects are already been sorted into non-increasing order of  $p[i] / w[i]$  then the algorithm given below obtains solutions corresponding to this strategy.

### **Algorithm GreedyKnapsack (m, n)**

```
// P[1 : n] and w[1 : n] contain the profits and weights respectively of
// Objects ordered so that p[i] / w[i] > p[i + 1] / w[i + 1].
// m is the knapsack size and x[1: n] is the solution vector.
{
    for i := 1 to n do x[i] := 0.0 // initialize x
    U := m;
    for i := 1 to n do
    {
        if (w(i) > U) then break;
        x [i] := 1.0; U := U - w[i];
    }
    if (i ≤ n) then x[i] := U / w[i];
}
```

### **Running time:**

The objects are to be sorted into non-decreasing order of  $p_i / w_i$  ratio. But if we disregard the time to initially sort the objects, the algorithm requires only  $O(n)$  time.

### **Example:**

Consider the following instance of the knapsack problem:  $n = 3$ ,  $m = 20$ ,  $(p_1, p_2, p_3) = (25, 24, 15)$  and  $(w_1, w_2, w_3) = (18, 15, 10)$ .

1. First, we try to fill the knapsack by selecting the objects in some order:

$x_1$	$x_2$	$x_3$	$\sum w_i x_i$	$\sum p_i x_i$
1/2	1/3	1/4	$18 \times 1/2 + 15 \times 1/3 + 10 \times 1/4 = 16.5$	$25 \times 1/2 + 24 \times 1/3 + 15 \times 1/4 = 24.25$

2. Select the object with the maximum profit first ( $p = 25$ ). So,  $x_1 = 1$  and profit earned is 25. Now, only 2 units of space is left, select the object with next largest profit ( $p = 24$ ). So,  $x_2 = 2/15$

$x_1$	$x_2$	$x_3$	$\sum w_i x_i$	$\sum p_i x_i$
1	2/15	0	$18 \times 1 + 15 \times 2/15 = 20$	$25 \times 1 + 24 \times 2/15 = 28.2$

3. Considering the objects in the order of non-decreasing weights  $w_i$ .

$x_1$	$x_2$	$x_3$	$\sum w_i x_i$	$\sum p_i x_i$
0	2/3	1	$15 \times 2/3 + 10 \times 1 = 20$	$24 \times 2/3 + 15 \times 1 = 31$

4. Considered the objects in the order of the ratio  $p_i / w_i$ .

$p_1/w_1$	$p_2/w_2$	$p_3/w_3$
25/18	24/15	15/10
1.4	1.6	1.5

Sort the objects in order of the non-increasing order of the ratio  $p_i / x_i$ . Select the object with the maximum  $p_i / x_i$  ratio, so,  $x_2 = 1$  and profit earned is 24. Now, only 5 units of space is left, select the object with next largest  $p_i / x_i$  ratio, so  $x_3 = 1/2$  and the profit earned is 7.5.

$x_1$	$x_2$	$x_3$	$\sum w_i x_i$	$\sum p_i x_i$
0	1	1/2	$15 \times 1 + 10 \times 1/2 = 20$	$24 \times 1 + 15 \times 1/2 = 31.5$

This solution is the optimal solution.

## JOB SEQUENCING WITH DEADLINES:

When we are given a set of 'n' jobs. Associated with each Job i, deadline  $d_i \geq 0$  and profit  $P_i \geq 0$ . For any job 'i' the profit  $p_i$  is earned iff the job is completed by its deadline. Only one machine is available for processing jobs. An optimal solution is the feasible solution with maximum profit.

Sort the jobs in 'j' ordered by their deadlines. The array  $d [1 : n]$  is used to store the deadlines of the order of their  $p$ -values. The set of jobs  $j [1 : k]$  such that  $j [r], 1 \leq r \leq k$  are the jobs in 'j' and  $d (j[1]) \leq d (j[2]) \leq \dots \leq d (j[k])$ . To test whether  $J \cup \{i\}$  is feasible, we have just to insert  $i$  into  $J$  preserving the deadline ordering and then verify that  $d [j[r]] \leq r, 1 \leq r \leq k+1$ .

**Example:**

Let  $n = 4$ ,  $(P_1, P_2, P_3, P_4) = (100, 10, 15, 27)$  and  $(d_1 d_2 d_3 d_4) = (2, 1, 2, 1)$ . The feasible solutions and their values are:

S. No	Feasible Solution	Procuring sequence	Value	Remarks
1	1,2	2,1	110	
2	1,3	1,3 or 3,1	115	
3	1,4	4,1	127	<b>OPTIMAL</b>
4	2,3	2,3	25	
5	3,4	4,3	42	
6	1	1	100	
7	2	2	10	
8	3	3	15	
9	4	4	27	

The algorithm constructs an optimal set  $J$  of jobs that can be processed by their deadlines.

**Algorithm GreedyJob (d, J, n)**

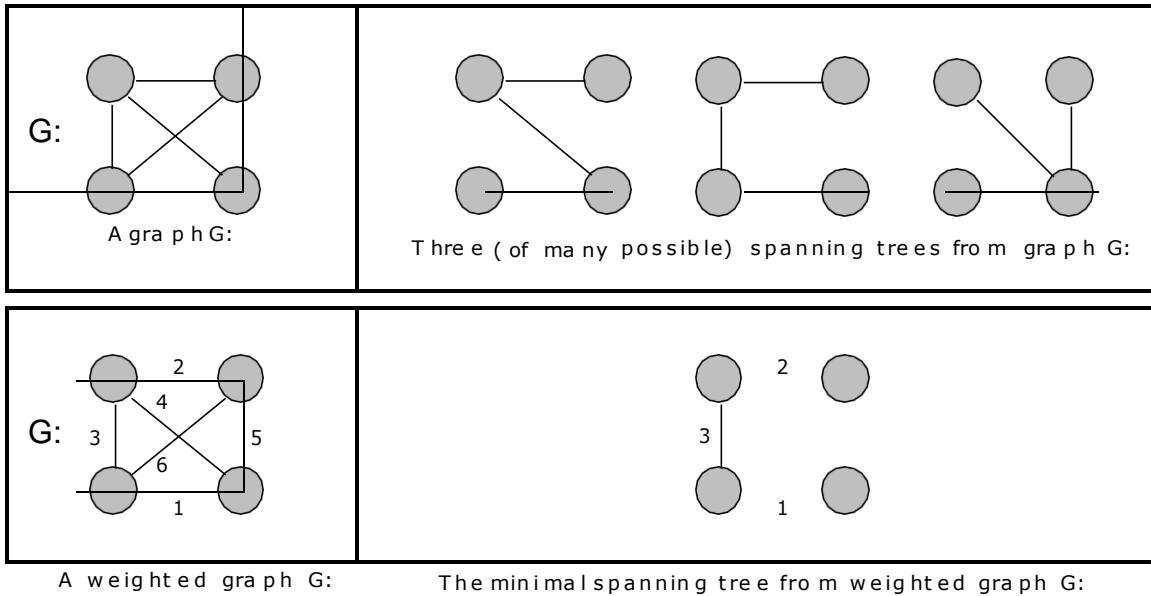
//  $J$  is a set of jobs that can be completed by their deadlines.

```
{
    J := {1};
    for i := 2 to n do
    {
        if (all jobs in J U {i} can be completed by their dead lines)
            then J := J U {i};
    }
}
```

**Minimum Spanning Trees (MST):**

A spanning tree for a connected graph is a tree whose vertex set is the same as the vertex set of the given graph, and whose edge set is a subset of the edge set of the given graph. i.e., any connected graph will have a spanning tree.

Weight of a spanning tree  $w(T)$  is the sum of weights of all edges in  $T$ . The Minimum spanning tree (MST) is a spanning tree with the smallest possible weight.



### Here are some examples:

To explain further upon the Minimum Spanning Tree, and what it applies to, let's consider a couple of real-world examples:

1. One practical application of a MST would be in the design of a network. For instance, a group of individuals, who are separated by varying distances, wish to be connected together in a telephone network. Although MST cannot do anything about the distance from one connection to another, it can be used to determine the least cost paths with no cycles in this network, thereby connecting everyone at a minimum cost.
2. Another useful application of MST would be finding airline routes. The vertices of the graph would represent cities, and the edges would represent routes between the cities. Obviously, the further one has to travel, the more it will cost, so MST can be applied to optimize airline routes by finding the least costly paths with no cycles.

To explain how to find a Minimum Spanning Tree, we will look at two algorithms: the Kruskal algorithm and the Prim algorithm. Both algorithms differ in their methodology, but both eventually end up with the MST. Kruskal's algorithm uses edges, and Prim's algorithm uses vertex connections in determining the MST.

### Kruskal's Algorithm

This is a greedy algorithm. A greedy algorithm chooses some local optimum (i.e. picking an edge with the least weight in a MST).

Kruskal's algorithm works as follows: Take a graph with ' $n$ ' vertices, keep on adding the shortest (least cost) edge, while avoiding the creation of cycles, until  $(n - 1)$  edges have been added. Sometimes two or more edges may have the same cost. The order in which the edges are chosen, in this case, does not matter. Different MSTs may result, but they will all have the same total cost, which will always be the minimum cost.

The algorithm for finding the MST, using the Kruskal's method is as follows:

### **Algorithm Kruskal (E, cost, n, t)**

```

// E is the set of edges in G. G has n vertices. cost [u, v] is the
// cost of edge (u, v). 't' is the set of edges in the minimum-cost spanning tree.
// The final cost is returned.
{
    Construct a heap out of the edge costs using heapify;
    for i := 1 to n do parent [i] := -1;                                // Each vertex is in a different set.
    i := 0; mincost := 0.0;
    while ((i < n - 1) and (heap not empty)) do
    {
        Delete a minimum cost edge (u, v) from the heap and
        re-heapify using Adjust;
        j := Find (u); k := Find (v);
        if (j ≠ k) then
        {
            i := i + 1;
            t [i, 1] := u; t [i, 2] := v;
            mincost := mincost + cost [u, v];
            Union (j, k);
        }
    }
    if (i ≠ n-1) then write ("no spanning tree");
    else return mincost;
}

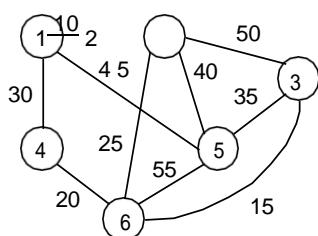
```

### **Running time:**

- The number of finds is at most  $2e$ , and the number of unions at most  $n-1$ . Including the initialization time for the trees, this part of the algorithm has a complexity that is just slightly more than  $O(n + e)$ .
- We can add at most  $n-1$  edges to tree  $T$ . So, the total time for operations on  $T$  is  $O(n)$ .

Summing up the various components of the computing times, we get  $O(n + e \log e)$  as asymptotic complexity

### **Example 1:**



Arrange all the edges in the increasing order of their costs:

Cost	10	15	20	25	30	35	40	45	50	55
Edge	(1, 2)	(3, 6)	(4, 6)	(2, 6)	(1, 4)	(3, 5)	(2, 5)	(1, 5)	(2, 3)	(5, 6)

The edge set T together with the vertices of G define a graph that has up to n connected components. Let us represent each component by a set of vertices in it. These vertex sets are disjoint. To determine whether the edge  $(u, v)$  creates a cycle, we need to check whether u and v are in the same vertex set. If so, then a cycle is created. If not then no cycle is created. Hence two **Finds** on the vertex sets suffice. When an edge is included in T, two components are combined into one and a **union** is to be performed on the two sets.

Edge	Cost	Spanning Forest	Edge Sets	Remarks
			{1}, {2}, {3}, {4}, {5}, {6}	
(1, 2)	10		{1, 2}, {3}, {4}, {5}, {6}	The vertices 1 and 2 are in different sets, so the edge is combined
(3, 6)	15		{1, 2}, {3, 6}, {4}, {5}	The vertices 3 and 6 are in different sets, so the edge is combined
(4, 6)	20		{1, 2}, {3, 4, 6}, {5}	The vertices 4 and 6 are in different sets, so the edge is combined
(2, 6)	25		{1, 2, 3, 4, 6}, {5}	The vertices 2 and 6 are in different sets, so the edge is combined
(1, 4)	30	Reject		The vertices 1 and 4 are in the same set, so the edge is rejected
(3, 5)	35		{1, 2, 3, 4, 5, 6}	The vertices 3 and 5 are in the same set, so the edge is combined

## MINIMUM-COST SPANNING TREES: PRIM'S ALGORITHM

A given graph can have many spanning trees. From these many spanning trees, we have to select a cheapest one. This tree is called as minimal cost spanning tree.

Minimal cost spanning tree is a connected undirected graph  $G$  in which each edge is labeled with a number (edge labels may signify lengths, weights other than costs). Minimal cost spanning tree is a spanning tree for which the sum of the edge labels is as small as possible

The slight modification of the spanning tree algorithm yields a very simple algorithm for finding an MST. In the spanning tree algorithm, any vertex not in the tree but connected to it by an edge can be added. To find a Minimal cost spanning tree, we must be selective - we must always add a new vertex for which the cost of the new edge is as small as possible.

This simple modified algorithm of spanning tree is called prim's algorithm for finding an Minimal cost spanning tree.

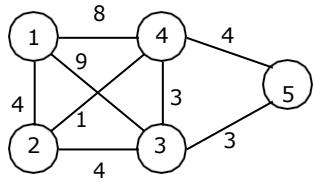
Prim's algorithm is an example of a greedy algorithm.

### Algorithm Prim ( $E$ , $cost$ , $n$ , $t$ )

```
// E is the set of edges in G. cost [1:n, 1:n] is the cost
// adjacency matrix of an n vertex graph such that cost [i, j] is
// either a positive real number or  $\infty$  if no edge (i, j) exists.
// A minimum spanning tree is computed and stored as a set of
// edges in the array t [1:n-1, 1:2]. (t [i, 1], t [i, 2]) is an edge in
// the minimum-cost spanning tree. The final cost is returned.
{
    Let (k, l) be an edge of minimum cost in E;
    mincost := cost [k, l];
    t [1, 1] := k; t [1, 2] := l;
    for i := 1 to n do                                // Initialize near
        if (cost [i, l] < cost [i, k]) then near [i] := l;
        else near [i] := k;
    near [k] := near [l] := 0;
    for i := 2 to n - 1 do                            // Find n - 2 additional edges for t.
    {
        Let j be an index such that near [j] ≠ 0 and
        cost [j, near [j]] is minimum;
        t [i, 1] := j; t [i, 2] := near [j];
        mincost := mincost + cost [j, near [j]];
        near [j] := 0
        for k := 1 to n do                            // Update near[].
            if ((near [k] ≠ 0) and (cost [k, near [k]] > cost [k, j]))
                then near [k] := j;
    }
    return mincost;
}
```

## Example:

Considering the following graph, find the minimal spanning tree using prim's algorithm.

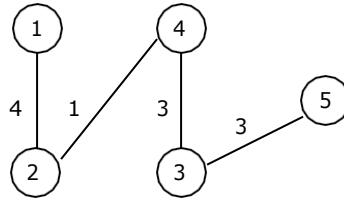


The cost adjacent matrix is

$$\begin{pmatrix} \infty & 4 & 9 & 8 & \infty \\ 4 & \infty & 4 & 1 & \infty \\ 9 & 4 & \infty & 3 & 3 \\ 8 & 1 & 3 & \infty & 4 \\ \infty & \infty & 3 & 4 & \infty \end{pmatrix}$$

The minimal spanning tree obtained as:

Vertex 1	Vertex 2
2	4
3	4
5	3
1	2



**The cost of Minimal spanning tree = 11.**

The steps as per the algorithm are as follows:

Algorithm near ( $J$ ) =  $k$  means, the nearest vertex to  $J$  is  $k$ .

The algorithm starts by selecting the minimum cost from the graph. The minimum cost edge is (2, 4).

$$K = 2, l = 4$$

$$\text{Min cost} = \text{cost}(2, 4) = 1$$

$$T[1, 1] = 2$$

$$T[1, 2] = 4$$

<pre> for i = 1 to 5 Begin i = 1 is cost (1, 4) &lt; cost (1, 2) 8 &lt; 4, No Than near (1) = 2  i = 2 is cost (2, 4) &lt; cost (2, 2) 1 &lt; ∞, Yes So near [2] = 4  i = 3 is cost (3, 4) &lt; cost (3, 2) 1 &lt; 4, Yes So near [3] = 4  i = 4 is cost (4, 4) &lt; cost (4, 2) ∞ &lt; 1, no So near [4] = 2  i = 5 is cost (5, 4) &lt; cost (5, 2) 4 &lt; ∞, yes So near [5] = 4  end  near [k] = near [l] = 0 near [2] = near[4] = 0 </pre>	<p style="text-align: center;">Near matrix</p> <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>2</td><td></td><td></td><td></td><td></td> </tr> <tr> <td>1</td><td>2</td><td>3</td><td>4</td><td>5</td> </tr> </table> <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>2</td><td>4</td><td></td><td></td><td></td> </tr> <tr> <td>1</td><td>2</td><td>3</td><td>4</td><td>5</td> </tr> </table> <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>2</td><td>4</td><td>4</td><td></td><td></td> </tr> <tr> <td>1</td><td>2</td><td>3</td><td>4</td><td>5</td> </tr> </table> <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>2</td><td>4</td><td>4</td><td>2</td><td></td> </tr> <tr> <td>1</td><td>2</td><td>3</td><td>4</td><td>5</td> </tr> </table> <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>2</td><td>4</td><td>4</td><td>2</td><td>4</td> </tr> <tr> <td>1</td><td>2</td><td>3</td><td>4</td><td>5</td> </tr> </table> <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>2</td><td>0</td><td>4</td><td>0</td><td>4</td> </tr> <tr> <td>1</td><td>2</td><td>3</td><td>4</td><td>5</td> </tr> </table>	2					1	2	3	4	5	2	4				1	2	3	4	5	2	4	4			1	2	3	4	5	2	4	4	2		1	2	3	4	5	2	4	4	2	4	1	2	3	4	5	2	0	4	0	4	1	2	3	4	5	<p>Edges added to min spanning tree:</p> <p><math>T[1, 1] = 2</math>  <math>T[1, 2] = 4</math></p>
2																																																														
1	2	3	4	5																																																										
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<pre> for i = 2 to n-1 (4) do <u>i=2</u>  for j = 1 to 5 j = 1 near(1)≠0 and cost(1, near(1)) 2 ≠ 0 and cost (1, 2) = 4  j = 2 near (2) = 0  j = 3 is near (3) ≠ 0 4 ≠ 0 and cost (3, 4) = 3 </pre>		
---	--	--

$j = 4$   
near (4) = 0

$J = 5$   
Is near (5) ≠ 0  
 $4 \neq 0$  and cost (4, 5) = 4

select the min cost from the above obtained costs, which is 3 and corresponding  $J = 3$

$$\begin{aligned} \text{min cost} &= 1 + \text{cost}(3, 4) \\ &= 1 + 3 = 4 \end{aligned}$$

$$\begin{aligned} T(2, 1) &= 3 \\ T(2, 2) &= 4 \end{aligned}$$

$$\begin{aligned} \text{Near}[j] &= 0 \\ \text{i.e. near}(3) &= 0 \end{aligned}$$

2	0	0	0	4
1	2	3	4	5

$$\begin{aligned} T(2, 1) &= 3 \\ T(2, 2) &= 4 \end{aligned}$$

for (k = 1 to n)

$K = 1$   
is near (1) ≠ 0, yes  
 $2 \neq 0$   
and cost (1,2) > cost(1, 3)  
 $4 > 9$ , No

$K = 2$   
Is near (2) ≠ 0, No

$K = 3$   
Is near (3) ≠ 0, No

$K = 4$   
Is near (4) ≠ 0, No

$K = 5$   
Is near (5) ≠ 0  
 $4 \neq 0$ , yes  
and is cost (5, 4) > cost (5, 3)  
 $4 > 3$ , yes  
than near (5) = 3

2	0	0	0	3
1	2	3	4	5

i = 3

for (j = 1 to 5)

$J = 1$   
is near (1) ≠ 0  
 $2 \neq 0$   
cost (1, 2) = 4

$J = 2$   
Is near (2) ≠ 0, No

$J = 3$   
 Is near (3)  $\neq 0$ , no  
 Near (3) = 0  
  
 $J = 4$   
 Is near (4)  $\neq 0$ , no  
 Near (4) = 0  
  
 $J = 5$   
 Is near (5)  $\neq 0$   
 Near (5) = 3  $\rightarrow 3 \neq 0$ , yes  
 And cost (5, 3) = 3  
  
 Choosing the min cost from  
 the above obtaining costs  
 which is 3 and corresponding J  
 = 5  
  
 Min cost = 4 + cost (5, 3)  
 = 4 + 3 = 7  
  
 $T(3, 1) = 5$   
 $T(3, 2) = 3$   
  
 $Near(J) = 0 \rightarrow near(5) = 0$   
for (k=1 to 5)  
  
 $k = 1$   
 is near (1)  $\neq 0$ , yes  
 and cost(1,2) > cost(1,5)  
 $4 > \infty$ , No  
  
 $K = 2$   
 Is near (2)  $\neq 0$  no  
  
 $K = 3$   
 Is near (3)  $\neq 0$  no  
  
 $K = 4$   
 Is near (4)  $\neq 0$  no  
  
 $K = 5$   
 Is near (5)  $\neq 0$  no  
  
**i = 4**  
for J = 1 to 5  
 $J = 1$   
 Is near (1)  $\neq 0$   
 $2 \neq 0$ , yes  
 cost (1, 2) = 4  
  
 $j = 2$   
 is near (2)  $\neq 0$ , No

2	0	0	0	0
1	2	3	4	5

$$T(3, 1) = 5$$

$$T(3, 2) = 3$$

<p>J = 3      Is near (3) ≠ 0, No      Near (3) = 0</p> <p>J = 4      Is near (4) ≠ 0, No      Near (4) = 0</p> <p>J = 5      Is near (5) ≠ 0, No      Near (5) = 0</p> <p>Choosing min cost from the above it is only '4' and corresponding J = 1</p> <p>Min cost = 7 + cost (1,2)  <math>= 7+4 = 11</math></p> <p><math>T(4, 1) = 1</math>  <math>T(4, 2) = 2</math></p> <p>Near (J) = 0 → Near (1) = 0</p> <p><u>for (k = 1 to 5)</u></p> <p>K = 1      Is near (1) ≠ 0, No</p> <p>K = 2      Is near (2) ≠ 0, No</p> <p>K = 3      Is near (3) ≠ 0, No</p> <p>K = 4      Is near (4) ≠ 0, No</p> <p>K = 5      Is near (5) ≠ 0, No</p> <p>End.</p>	<table border="1" data-bbox="647 729 1029 808"> <tr> <td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr> </table> <p style="text-align: center;">1      2      3      4      5</p>	0	0	0	0	0	<p><math>T(4, 1) = 1</math>  <math>T(4, 2) = 2</math></p>
0	0	0	0	0			

### The Single Source Shortest-Path Problem: DIJKSTRA'S ALGORITHMS:

In the previously studied graphs, the edge labels are called as costs, but here we think them as lengths. In a labeled graph, the length of the path is defined to be the sum of the lengths of its edges.

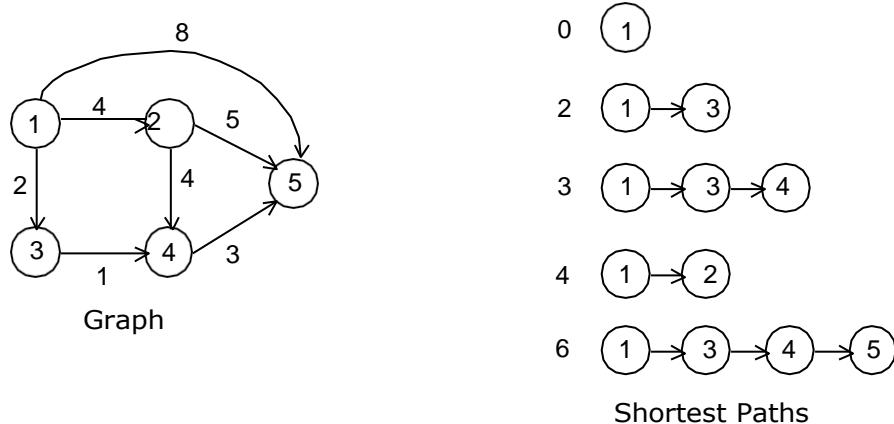
*In the single source, all destinations, shortest path problem, we must find a shortest path from a given source vertex to each of the vertices (called destinations) in the graph to which there is a path.*

Dijkstra's algorithm is similar to prim's algorithm for finding minimal spanning trees. Dijkstra's algorithm takes a labeled graph and a pair of vertices P and Q, and finds the

shortest path between them (or one of the shortest paths) if there is more than one. The principle of optimality is the basis for Dijkstra's algorithms.

Dijkstra's algorithm does not work for negative edges at all.

The figure lists the shortest paths from vertex 1 for a five vertex weighted digraph.



### Algorithm:

```

Algorithm Shortest-Paths (v, cost, dist, n)
// dist [j], 1 ≤ j ≤ n, is set to the length of the shortest path
// from vertex v to vertex j in the digraph G with n vertices.
// dist [v] is set to zero. G is represented by its
// cost adjacency matrix cost [1:n, 1:n].
{
    for i :=1 to n do
    {
        S [i] := false;                                // Initialize S.
        dist [i] :=cost [v, i];
    }
    S[v] := true; dist[v] := 0.0;                      // Put v in S.
    for num := 2 to n - 1 do
    {
        Determine n - 1 paths from v.
        Choose u from among those vertices not in S such that dist[u] is minimum;
        S[u] := true;                                // Put u in S.
        for (each w adjacent to u with S [w] = false) do
            if (dist [w] > (dist [u] + cost [u, w])) then // Update distances
                dist [w] := dist [u] + cost [u,w];
    }
}

```

### Running time:

Depends on implementation of data structures for dist.

- Build a structure with  $n$  elements A
- at most  $m = |E|$  times decrease the value of an item mB
- ' $n$ ' times select the smallest value nC
- For array A =  $O(n)$ ; B =  $O(1)$ ; C =  $O(n)$  which gives  $O(n^2)$  total.
- For heap A =  $O(n)$ ; B =  $O(\log n)$ ; C =  $O(\log n)$  which gives  $O(n + m \log n)$  total.

**UNIT III:**

**Dynamic Programming:** General method, applications-Matrix chain multiplication, Multi stage graphs, Optimal binary search trees, 0/1 knapsack problem, All pairs shortest path problem, Travelling sales person problem, Reliability design.

## Dynamic Programming

Dynamic programming is a name, coined by Richard Bellman in 1955. Dynamic programming, as greedy method, is a powerful algorithm design technique that can be used when the solution to the problem may be viewed as the result of a sequence of decisions. In the greedy method we make irrevocable decisions one at a time, using a greedy criterion. However, in dynamic programming we examine the decision sequence to see whether an optimal decision sequence contains optimal decision subsequences.

When optimal decision sequences contain optimal decision subsequences, we can establish recurrence equations, called *dynamic-programming recurrence equations*, that enable us to solve the problem in an efficient way.

Dynamic programming is based on the principle of optimality (also coined by Bellman). The principle of optimality states that no matter whatever the initial state and initial decision are, the remaining decision sequence must constitute an optimal decision sequence with regard to the state resulting from the first decision. The principle implies that an optimal decision sequence is comprised of optimal decision subsequences. Since the principle of optimality may not hold for some formulations of some problems, it is necessary to verify that it does hold for the problem being solved. Dynamic programming cannot be applied when this principle does not hold.

The steps in a dynamic programming solution are:

- Verify that the principle of optimality holds
- Set up the dynamic-programming recurrence equations
- Solve the dynamic-programming recurrence equations for the value of the optimal solution.
- Perform a trace back step in which the solution itself is constructed.

Dynamic programming differs from the greedy method since the greedy method produces only one feasible solution, which may or may not be optimal, while dynamic programming produces all possible sub-problems at most once, one of which guaranteed to be optimal. Optimal solutions to sub-problems are retained in a table, thereby avoiding the work of recomputing the answer every time a sub-problem is encountered

The divide and conquer principle solve a large problem, by breaking it up into smaller problems which can be solved independently. In dynamic programming this principle is carried to an extreme: when we don't know exactly which smaller problems to solve, we simply solve them all, then store the answers away in a table to be used later in solving larger problems. Care is to be taken to avoid recomputing previously

computed values, otherwise the recursive program will have prohibitive complexity. In some cases, the solution can be improved and in other cases, the dynamic programming technique is the best approach.

Two difficulties may arise in any application of dynamic programming:

1. It may not always be possible to combine the solutions of smaller problems to form the solution of a larger one.
2. The number of small problems to solve may be un-acceptably large.

There is no characterized precisely which problems can be effectively solved with dynamic programming; there are many hard problems for which it does not seem to be applicable, as well as many easy problems for which it is less efficient than standard algorithms.

## MULTI STAGE GRAPHS:

A multistage graph  $G = (V, E)$  is a directed graph in which the vertices are partitioned into  $k \geq 2$  disjoint sets  $V_i$ ,  $1 \leq i \leq k$ . In addition, if  $\langle u, v \rangle$  is an edge in  $E$ , then  $u \in V_i$  and  $v \in V_{i+1}$  for some  $i$ ,  $1 \leq i < k$ .

Let the vertex 's' is the source, and 't' the sink. Let  $c(i, j)$  be the cost of edge  $\langle i, j \rangle$ . The cost of a path from 's' to 't' is the sum of the costs of the edges on the path. The multistage graph problem is to find a minimum cost path from 's' to 't'. Each set  $V_i$  defines a stage in the graph. Because of the constraints on  $E$ , every path from 's' to 't' starts in stage 1, goes to stage 2, then to stage 3, then to stage 4, and so on, and eventually terminates in stage  $k$ .

A dynamic programming formulation for a  $k$ -stage graph problem is obtained by first noticing that every  $s$  to  $t$  path is the result of a sequence of  $k - 2$  decisions. The  $i^{\text{th}}$  decision involves determining which vertex in  $V_{i+1}$ ,  $1 \leq i \leq k - 2$ , is to be on the path. Let  $c(i, j)$  be the cost of the path from source to destination. Then using the forward approach, we obtain:

$$\text{cost}(i, j) = \min_{\substack{l \in V_{i+1} \\ \langle j, l \rangle \in E}} \{c(j, l) + \text{cost}(i + 1, l)\}$$

## ALGORITHM:

### Algorithm Fgraph ( $G, k, n, p$ )

```
// The input is a k-stage graph G = (V, E) with n vertices
// indexed in order or stages. E is a set of edges and c [i, j]
// is the cost of (i, j). p [1 : k] is a minimum cost path.
{
    cost [n] := 0.0;
    for j := n - 1 to 1 step -1 do
    {
        let r be a vertex such that (j, r) is an edge
        of G and c [j, r] + cost [r] is minimum;
        cost [j] := c [j, r] + cost [r];
        d [j] := r;
    }
    p [1] := 1; p [k] := n; // Find a minimum cost path.
    for j := 2 to k - 1 do p [j] := d [p [j - 1]];
}
```

The multistage graph problem can also be solved using the backward approach. Let  $bp(i, j)$  be a minimum cost path from vertex  $s$  to  $j$  vertex in  $V_i$ . Let  $Bcost(i, j)$  be the cost of  $bp(i, j)$ . From the backward approach we obtain:

$$Bcost(i, j) = \min \{ Bcost(i-1, l) + c(l, j) \mid l \in V_{i-1} \}$$

### **Algorithm Bgraph** ( $G, k, n, p$ )

// Same function as Fgraph

77

```
Bcost [1] := 0.0;  
for j := 2 to n do
```

Let  $r$  be such that  $(r, j)$  is an edge of  
 $G$  and  $Bcost[r] + c[r, j]$  is minimum;  
 $Bcost[j] := Bcost[r] + c[r, j];$   
 $D[j] := r;$

```

} //find a minimum cost path
p [1] := 1; p [k] := n;
for j:= k - 1 to 2 do p [j] := d [p [j + 1]];

```

For  $j \in R$ ,  $\Gamma = \text{col}(\mathbf{P}_{[j]})^T \cdot \mathbf{d}[\mathbf{P}_{[j]}^T \cdot \mathbf{z}]$ ,

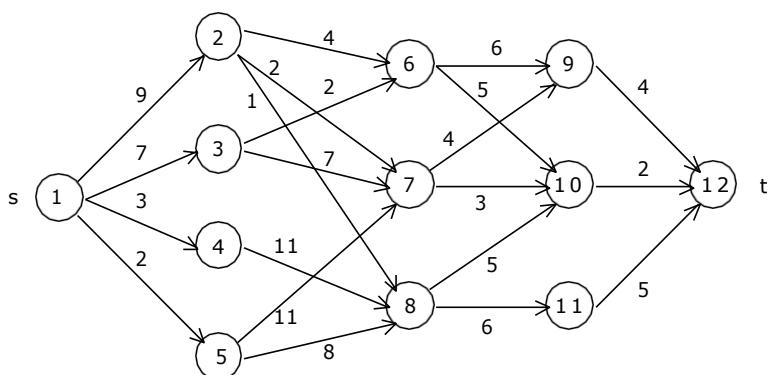
}

## Complexity Analysis:

The complexity analysis of the algorithm is fairly straightforward. Here, if G has  $|E|$  edges, then the time for the first for loop is  $\Phi(|V| + |E|)$ .

## **EXAMPLE:**

Find the minimum cost path from  $s$  to  $t$  in the multistage graph of five stages shown below. Do this first using forward approach and then using backward approach.



## **FORWARD APPROACH:**

We use the following equation to find the minimum cost path from  $s$  to  $t$ :

$$\text{cost}(i, j) = \min_{l \in V_{i+1}} \{c(j, l) + \text{cost}(i+1, l)\}$$

$\langle j, l \rangle \in E$

$$\begin{aligned} \text{cost}(1, 1) &= \min \{c(1, 2) + \text{cost}(2, 2), c(1, 3) + \text{cost}(2, 3), c(1, 4) + \text{cost}(2, 4), \\ &\quad c(1, 5) + \text{cost}(2, 5)\} \\ &= \min \{9 + \text{cost}(2, 2), 7 + \text{cost}(2, 3), 3 + \text{cost}(2, 4), 2 + \text{cost}(2, 5)\} \end{aligned}$$

Now first starting with,

$$\begin{aligned}\text{cost } (2, 2) &= \min\{c(2, 6) + \text{cost}(3, 6), c(2, 7) + \text{cost}(3, 7), c(2, 8) + \text{cost}(3, 8)\} \\ &= \min\{4 + \text{cost}(3, 6), 2 + \text{cost}(3, 7), 1 + \text{cost}(3, 8)\}\end{aligned}$$

---

$$\begin{aligned}\text{cost } (3, 6) &= \min\{c(6, 9) + \text{cost}(4, 9), c(6, 10) + \text{cost}(4, 10)\} \\ &= \min\{6 + \text{cost}(4, 9), 5 + \text{cost}(4, 10)\}\end{aligned}$$

$$\text{cost } (4, 9) = \min\{c(9, 12) + \text{cost}(5, 12)\} = \min\{4 + 0\} = 4$$

$$\text{cost } (4, 10) = \min\{c(10, 12) + \text{cost}(5, 12)\} = 2$$

$$\text{Therefore, cost } (3, 6) = \min\{6 + 4, 5 + 2\} = 7$$

---

$$\begin{aligned}\text{cost } (3, 7) &= \min\{c(7, 9) + \text{cost}(4, 9), c(7, 10) + \text{cost}(4, 10)\} \\ &= \min\{4 + \text{cost}(4, 9), 3 + \text{cost}(4, 10)\}\end{aligned}$$

$$\text{cost } (4, 9) = \min\{c(9, 12) + \text{cost}(5, 12)\} = \min\{4 + 0\} = 4$$

$$\text{Cost } (4, 10) = \min\{c(10, 12) + \text{cost}(5, 12)\} = \min\{2 + 0\} = 2$$

$$\text{Therefore, cost } (3, 7) = \min\{4 + 4, 3 + 2\} = \min\{8, 5\} = 5$$

---

$$\begin{aligned}\text{cost } (3, 8) &= \min\{c(8, 10) + \text{cost}(4, 10), c(8, 11) + \text{cost}(4, 11)\} \\ &= \min\{5 + \text{cost}(4, 10), 6 + \text{cost}(4, 11)\}\end{aligned}$$

$$\text{cost } (4, 11) = \min\{c(11, 12) + \text{cost}(5, 12)\} = 5$$

$$\text{Therefore, cost } (3, 8) = \min\{5 + 2, 6 + 5\} = \min\{7, 11\} = 7$$

---

$$\text{Therefore, cost } (2, 2) = \min\{4 + 7, 2 + 5, 1 + 7\} = \min\{11, 7, 8\} = 7$$

---

$$\begin{aligned}\text{Therefore, cost } (2, 3) &= \min\{c(3, 6) + \text{cost}(3, 6), c(3, 7) + \text{cost}(3, 7)\} \\ &= \min\{2 + \text{cost}(3, 6), 7 + \text{cost}(3, 7)\} \\ &= \min\{2 + 7, 7 + 5\} = \min\{9, 12\} = 9\end{aligned}$$

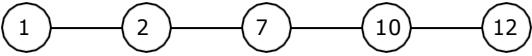
$$\text{cost } (2, 4) = \min\{c(4, 8) + \text{cost}(3, 8)\} = \min\{11 + 7\} = 18$$

$$\begin{aligned}\text{cost } (2, 5) &= \min\{c(5, 7) + \text{cost}(3, 7), c(5, 8) + \text{cost}(3, 8)\} \\ &= \min\{11 + 5, 8 + 7\} = \min\{16, 15\} = 15\end{aligned}$$

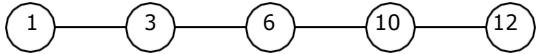
---

$$\begin{aligned}\text{Therefore, cost } (1, 1) &= \min\{9 + 7, 7 + 9, 3 + 18, 2 + 15\} \\ &= \min\{16, 16, 21, 17\} = 16\end{aligned}$$

The minimum cost path is 16.

The path is 

**or**



### BACKWARD APPROACH:

We use the following equation to find the minimum cost path from t to s:

$$Bcost(i, j) = \min_{\substack{i \in V_{i-1} \\ \langle i, j \rangle \in E}} \{Bcost(i-1, l) + c(l, j)\}$$

$$\begin{aligned} Bcost(5, 12) &= \min \{Bcost(4, 9) + c(9, 12), Bcost(4, 10) + c(10, 12), \\ &\quad Bcost(4, 11) + c(11, 12)\} \\ &= \min \{Bcost(4, 9) + 4, Bcost(4, 10) + 2, Bcost(4, 11) + 5\} \end{aligned}$$

$$\begin{aligned} Bcost(4, 9) &= \min \{Bcost(3, 6) + c(6, 9), Bcost(3, 7) + c(7, 9)\} \\ &= \min \{Bcost(3, 6) + 6, Bcost(3, 7) + 4\} \end{aligned}$$

$$\begin{aligned} Bcost(3, 6) &= \min \{Bcost(2, 2) + c(2, 6), Bcost(2, 3) + c(3, 6)\} \\ &= \min \{Bcost(2, 2) + 4, Bcost(2, 3) + 2\} \end{aligned}$$

$$Bcost(2, 2) = \min \{Bcost(1, 1) + c(1, 2)\} = \min \{0 + 9\} = 9$$

$$Bcost(2, 3) = \min \{Bcost(1, 1) + c(1, 3)\} = \min \{0 + 7\} = 7$$

$$Bcost(3, 6) = \min \{9 + 4, 7 + 2\} = \min \{13, 9\} = 9$$

$$Bcost(3, 7) = \min \{Bcost(2, 2) + c(2, 7), Bcost(2, 3) + c(3, 7), \\ Bcost(2, 5) + c(5, 7)\}$$

$$Bcost(2, 5) = \min \{Bcost(1, 1) + c(1, 5)\} = 2$$

$$Bcost(3, 7) = \min \{9 + 2, 7 + 7, 2 + 11\} = \min \{11, 14, 13\} = 11$$

$$Bcost(4, 9) = \min \{9 + 6, 11 + 4\} = \min \{15, 15\} = 15$$

$$Bcost(4, 10) = \min \{Bcost(3, 6) + c(6, 10), Bcost(3, 7) + c(7, 10), \\ Bcost(3, 8) + c(8, 10)\}$$

$$Bcost(3, 8) = \min \{Bcost(2, 2) + c(2, 8), Bcost(2, 4) + c(4, 8), \\ Bcost(2, 5) + c(5, 8)\}$$

$$Bcost(2, 4) = \min \{Bcost(1, 1) + c(1, 4)\} = 3$$

$$Bcost(3, 8) = \min \{9 + 1, 3 + 11, 2 + 8\} = \min \{10, 14, 10\} = 10$$

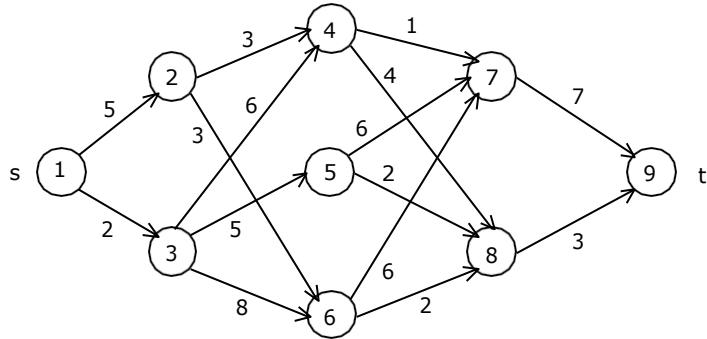
$$Bcost(4, 10) = \min \{9 + 5, 11 + 3, 10 + 5\} = \min \{14, 14, 15\} = 14$$

$$\begin{aligned} Bcost(4, 11) &= \min \{Bcost(3, 8) + c(8, 11)\} = \min \{Bcost(3, 8) + 6\} \\ &= \min \{10 + 6\} = 16 \end{aligned}$$

$$B\text{cost}(5, 12) = \min \{15 + 4, 14 + 2, 16 + 5\} = \min \{19, 16, 21\} = 16.$$

### EXAMPLE 2:

Find the minimum cost path from  $s$  to  $t$  in the multistage graph of five stages shown below. Do this first using forward approach and then using backward approach.



### SOLUTION:

#### FORWARD APPROACH:

$$\text{cost}(i, j) = \min_{\substack{l \in V_{i+1} \\ (j, l) \in E}} \{c(j, l) + \text{cost}(i+1, l)\}$$

$$\begin{aligned} \text{cost}(1, 1) &= \min \{c(1, 2) + \text{cost}(2, 2), c(1, 3) + \text{cost}(2, 3)\} \\ &= \min \{5 + \text{cost}(2, 2), 2 + \text{cost}(2, 3)\} \end{aligned}$$

$$\begin{aligned} \text{cost}(2, 2) &= \min \{c(2, 4) + \text{cost}(3, 4), c(2, 6) + \text{cost}(3, 6)\} \\ &= \min \{3 + \text{cost}(3, 4), 3 + \text{cost}(3, 6)\} \end{aligned}$$

$$\begin{aligned} \text{cost}(3, 4) &= \min \{c(4, 7) + \text{cost}(4, 7), c(4, 8) + \text{cost}(4, 8)\} \\ &= \min \{(1 + \text{cost}(4, 7)), 4 + \text{cost}(4, 8)\} \end{aligned}$$

$$\text{cost}(4, 7) = \min \{c(7, 9) + \text{cost}(5, 9)\} = \min \{7 + 0\} = 7$$

$$\text{cost}(4, 8) = \min \{c(8, 9) + \text{cost}(5, 9)\} = 3$$

$$\text{Therefore, } \text{cost}(3, 4) = \min \{8, 7\} = 7$$

$$\begin{aligned} \text{cost}(3, 6) &= \min \{c(6, 7) + \text{cost}(4, 7), c(6, 8) + \text{cost}(4, 8)\} \\ &= \min \{6 + \text{cost}(4, 7), 2 + \text{cost}(4, 8)\} = \min \{6 + 7, 2 + 3\} = 5 \end{aligned}$$

$$\text{Therefore, } \text{cost}(2, 2) = \min \{10, 8\} = 8$$

$$\text{cost}(2, 3) = \min \{c(3, 4) + \text{cost}(3, 4), c(3, 5) + \text{cost}(3, 5), c(3, 6) + \text{cost}(3, 6)\}$$

$$\begin{aligned} \text{cost}(3, 5) &= \min \{c(5, 7) + \text{cost}(4, 7), c(5, 8) + \text{cost}(4, 8)\} = \min \{6 + 7, 2 + 3\} \\ &= 5 \end{aligned}$$

$$\text{Therefore, } \text{cost}(2, 3) = \min \{13, 10, 13\} = 10$$

$$\text{cost}(1, 1) = \min \{5 + 8, 2 + 10\} = \min \{13, 12\} = 12$$

### **BACKWARD APPROACH:**

$$Bcost(i, j) = \min_{\substack{l \in V_{i-1} \\ <l, j> \in E}} \{Bcost(l, j) = c(l, j)\}$$

$$\begin{aligned} Bcost(5, 9) &= \min \{Bcost(4, 7) + c(7, 9), Bcost(4, 8) + c(8, 9)\} \\ &= \min \{Bcost(4, 7) + 7, Bcost(4, 8) + 3\} \end{aligned}$$

$$\begin{aligned} Bcost(4, 7) &= \min \{Bcost(3, 4) + c(4, 7), Bcost(3, 5) + c(5, 7), \\ &\quad Bcost(3, 6) + c(6, 7)\} \\ &= \min \{Bcost(3, 4) + 1, Bcost(3, 5) + 6, Bcost(3, 6) + 6\} \end{aligned}$$

$$\begin{aligned} Bcost(3, 4) &= \min \{Bcost(2, 2) + c(2, 4), Bcost(2, 3) + c(3, 4)\} \\ &= \min \{Bcost(2, 2) + 3, Bcost(2, 3) + 6\} \end{aligned}$$

$$Bcost(2, 2) = \min \{Bcost(1, 1) + c(1, 2)\} = \min \{0 + 5\} = 5$$

$$Bcost(2, 3) = \min \{Bcost(1, 1) + c(1, 3)\} = \min \{0 + 2\} = 2$$

$$\text{Therefore, } Bcost(3, 4) = \min \{5 + 3, 2 + 6\} = \min \{8, 8\} = 8$$

$$Bcost(3, 5) = \min \{Bcost(2, 3) + c(3, 5)\} = \min \{2 + 5\} = 7$$

$$\begin{aligned} Bcost(3, 6) &= \min \{Bcost(2, 2) + c(2, 6), Bcost(2, 3) + c(3, 6)\} \\ &= \min \{5 + 5, 2 + 8\} = 10 \end{aligned}$$

$$\text{Therefore, } Bcost(4, 7) = \min \{8 + 1, 7 + 6, 10 + 6\} = 9$$

$$\begin{aligned} Bcost(4, 8) &= \min \{Bcost(3, 4) + c(4, 8), Bcost(3, 5) + c(5, 8), \\ &\quad Bcost(3, 6) + c(6, 8)\} \\ &= \min \{8 + 4, 7 + 2, 10 + 2\} = 9 \end{aligned}$$

$$\text{Therefore, } Bcost(5, 9) = \min \{9 + 7, 9 + 3\} = 12$$

### **All pairs shortest paths:**

In the all pairs shortest path problem, we are to find a shortest path between every pair of vertices in a directed graph G. That is, for every pair of vertices (i, j), we are to find a shortest path from i to j as well as one from j to i. These two paths are the same when G is undirected.

When no edge has a negative length, the all-pairs shortest path problem may be solved by using Dijkstra's greedy single source algorithm n times, once with each of the n vertices as the source vertex.

The all pairs shortest path problem is to determine a matrix A such that A(i, j) is the length of a shortest path from i to j. The matrix A can be obtained by solving n single-source problems using the algorithm shortest Paths. Since each application of this procedure requires O(n<sup>2</sup>) time, the matrix A can be obtained in O(n<sup>3</sup>) time.

The dynamic programming solution, called Floyd's algorithm, runs in  $O(n^3)$  time. Floyd's algorithm works even when the graph has negative length edges (provided there are no negative length cycles).

The shortest  $i$  to  $j$  path in  $G$ ,  $i \neq j$  originates at vertex  $i$  and goes through some intermediate vertices (possibly none) and terminates at vertex  $j$ . If  $k$  is an intermediate vertex on this shortest path, then the subpaths from  $i$  to  $k$  and from  $k$  to  $j$  must be shortest paths from  $i$  to  $k$  and  $k$  to  $j$ , respectively. Otherwise, the  $i$  to  $j$  path is not of minimum length. So, the principle of optimality holds. Let  $A^k(i, j)$  represent the length of a shortest path from  $i$  to  $j$  going through no vertex of index greater than  $k$ , we obtain:

$$A^k(i, j) = \min_{1 \leq k \leq n} \{ \min \{ A^{k-1}(i, k) + A^{k-1}(k, j), c(i, j) \} \}$$

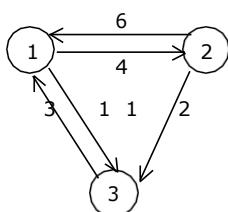
### **Algorithm All Paths (Cost, A, n)**

```
// cost [1:n, 1:n] is the cost adjacency matrix of a graph which
// n vertices; A [i, j] is the cost of a shortest path from vertex
// i to vertex j. cost [i, i] = 0.0, for 1 ≤ i ≤ n.
{
    for i := 1 to n do
        for j := 1 to n do
            A [i, j] := cost [i, j]; // copy cost into A.
    for k := 1 to n do
        for i := 1 to n do
            for j := 1 to n do
                A [i, j] := min (A [i, j], A [i, k] + A [k, j]);
}
}
```

**Complexity Analysis:** A Dynamic programming algorithm based on this recurrence involves in calculating  $n+1$  matrices, each of size  $n \times n$ . Therefore, the algorithm has a complexity of  $O(n^3)$ .

### **Example 1:**

Given a weighted digraph  $G = (V, E)$  with weight. Determine the length of the shortest path between all pairs of vertices in  $G$ . Here we assume that there are no cycles with zero or negative cost.



Cost adjacency matrix ( $A^0$ ) =  $\begin{bmatrix} 0 & 4 & 11 \\ 6 & 0 & 2 \\ 3 & \infty & 0 \end{bmatrix}$

General formula:  $\min_{1 \leq k \leq n} \{ A^{k-1}(i, k) + A^{k-1}(k, j), c(i, j) \}$

Solve the problem for different values of  $k = 1, 2$  and  $3$

**Step 1:** Solving the equation for,  $k = 1$ ;

$$\begin{aligned}
A^1(1,1) &= \min \{(A^0(1,1) + A^0(1,1)), c(1,1)\} = \min \{0 + 0, 0\} = 0 \\
A^1(1,2) &= \min \{(A^0(1,1) + A^0(1,2)), c(1,2)\} = \min \{(0 + 4), 4\} = 4 \\
A^1(1,3) &= \min \{(A^0(1,1) + A^0(1,3)), c(1,3)\} = \min \{(0 + 11), 11\} = 11 \\
A^1(2,1) &= \min \{(A^0(2,1) + A^0(1,1)), c(2,1)\} = \min \{(6 + 0), 6\} = 6 \\
A^1(2,2) &= \min \{(A^0(2,1) + A^0(1,2)), c(2,2)\} = \min \{(6 + 4), 0\} = 0 \\
A^1(2,3) &= \min \{(A^0(2,1) + A^0(1,3)), c(2,3)\} = \min \{(6 + 11), 2\} = 2 \\
A^1(3,1) &= \min \{(A^0(3,1) + A^0(1,1)), c(3,1)\} = \min \{(3 + 0), 3\} = 3 \\
A^1(3,2) &= \min \{(A^0(3,1) + A^0(1,2)), c(3,2)\} = \min \{(3 + 4), \infty\} = 7 \\
A^1(3,3) &= \min \{(A^0(3,1) + A^0(1,3)), c(3,3)\} = \min \{(3 + 11), 0\} = 0
\end{aligned}$$

$$A^{(1)} = \begin{bmatrix} 0 & 4 & 11 \\ 6 & 0 & 2 \\ 3 & 7 & 0 \end{bmatrix}$$

**Step 2:** Solving the equation for, K = 2;

$$\begin{aligned}
A^2(1,1) &= \min \{(A^1(1,2) + A^1(2,1)), c(1,1)\} = \min \{(4 + 6), 0\} = 0 \\
A^2(1,2) &= \min \{(A^1(1,2) + A^1(2,2)), c(1,2)\} = \min \{(4 + 0), 4\} = 4 \\
A^2(1,3) &= \min \{(A^1(1,2) + A^1(2,3)), c(1,3)\} = \min \{(4 + 2), 11\} = 6 \\
A^2(2,1) &= \min \{(A(2,2) + A(2,1)), c(2,1)\} = \min \{(0 + 6), 6\} = 6 \\
A^2(2,2) &= \min \{(A(2,2) + A(2,2)), c(2,2)\} = \min \{(0 + 0), 0\} = 0 \\
A^2(2,3) &= \min \{(A(2,2) + A(2,3)), c(2,3)\} = \min \{(0 + 2), 2\} = 2 \\
A^2(3,1) &= \min \{(A(3,2) + A(2,1)), c(3,1)\} = \min \{(7 + 6), 3\} = 3 \\
A^2(3,2) &= \min \{(A(3,2) + A(2,2)), c(3,2)\} = \min \{(7 + 0), 7\} = 7 \\
A^2(3,3) &= \min \{(A(3,2) + A(2,3)), c(3,3)\} = \min \{(7 + 2), 0\} = 0
\end{aligned}$$

$$A^{(2)} = \begin{bmatrix} 0 & 4 & 6 \\ 6 & 0 & 2 \\ 3 & 7 & 0 \end{bmatrix}$$

**Step 3:** Solving the equation for, k = 3;

$$\begin{aligned}
A^3(1,1) &= \min \{A^2(1,3) + A^2(3,1), c(1,1)\} = \min \{(6 + 3), 0\} = 0 \\
A^3(1,2) &= \min \{A^2(1,3) + A^2(3,2), c(1,2)\} = \min \{(6 + 7), 4\} = 4 \\
A^3(1,3) &= \min \{A^2(1,3) + A^2(3,3), c(1,3)\} = \min \{(6 + 0), 6\} = 6 \\
A^3(2,1) &= \min \{A^2(2,3) + A^2(3,1), c(2,1)\} = \min \{(2 + 3), 6\} = 5 \\
A^3(2,2) &= \min \{A^2(2,3) + A^2(3,2), c(2,2)\} = \min \{(2 + 7), 0\} = 0 \\
A^3(2,3) &= \min \{A^2(2,3) + A^2(3,3), c(2,3)\} = \min \{(2 + 0), 2\} = 2 \\
A^3(3,1) &= \min \{A^2(3,3) + A^2(3,1), c(3,1)\} = \min \{(0 + 3), 3\} = 3 \\
A^3(3,2) &= \min \{A^2(3,3) + A^2(3,2), c(3,2)\} = \min \{(0 + 7), 7\} = 7
\end{aligned}$$

$$A^3(3, 3) = \min \{A^2(3, 3) + A^2(3, 3), c(3, 3)\} = \min \{(0 + 0), 0\} = 0$$

$$A^{(3)} = \begin{bmatrix} 0 & 4 & 6 \\ 5 & 0 & 2 \\ 3 & 7 & 0 \end{bmatrix}$$

### TRAVELLING SALESPERSON PROBLEM:

Let  $G = (V, E)$  be a directed graph with edge costs  $C_{ij}$ . The variable  $c_{ij}$  is defined such that  $c_{ij} > 0$  for all  $i$  and  $j$  and  $c_{ij} = \alpha$  if  $\langle i, j \rangle \notin E$ . Let  $|V| = n$  and assume  $n > 1$ . A tour of  $G$  is a directed simple cycle that includes every vertex in  $V$ . The cost of a tour is the sum of the cost of the edges on the tour. The traveling sales person problem is to find a tour of minimum cost. The tour is to be a simple path that starts and ends at vertex 1.

Let  $g(i, S)$  be the length of shortest path starting at vertex  $i$ , going through all vertices in  $S$ , and terminating at vertex 1. The function  $g(1, V - \{1\})$  is the length of an optimal salesperson tour. From the principal of optimality it follows that:

$$g(1, V - \{1\}) = \min_{2 \leq k \leq n} \{c_{1k} + g(k, V - \{1, k\})\} \quad -- \quad 1$$

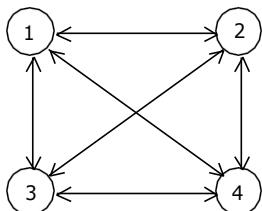
Generalizing equation 1, we obtain (for  $i \notin S$ )

$$g(i, S) = \min_{j \in S} \{c_{ij} + g(i, S - \{j\})\} \quad -- \quad 2$$

The Equation can be solved for  $g(1, V - 1)$  if we know  $g(k, V - \{1, k\})$  for all choices of  $k$ .

### Example :

For the following graph find minimum cost tour for the traveling salesperson problem:



The cost adjacency matrix =

$$\begin{bmatrix} 0 & 10 & 15 & 20 \\ 5 & 0 & 9 & 10 \\ 6 & 13 & 0 & 12 \\ 8 & 8 & 9 & 0 \end{bmatrix}$$

Let us start the tour from vertex 1:

$$g(1, V - \{1\}) = \min_{2 \leq k \leq n} \{c_{1k} + g(k, V - \{1, K\})\} \quad - \quad (1)$$

More generally writing:

$$g(i, s) = \min \{c_{ij} + g(j, s - \{j\})\} \quad - \quad (2)$$

Clearly,  $g(i, \Phi) = c_{i1}$ ,  $1 \leq i \leq n$ . So,

$$g(2, \Phi) = C_{21} = 5$$

$$g(3, \Phi) = C_{31} = 6$$

$$g(4, \Phi) = C_{41} = 8$$

Using equation – (2) we obtain:

$$g(1, \{2, 3, 4\}) = \min \{c_{12} + g(2, \{3, 4\}), c_{13} + g(3, \{2, 4\}), c_{14} + g(4, \{2, 3\})\}$$

$$\begin{aligned} g(2, \{3, 4\}) &= \min \{c_{23} + g(3, \{4\}), c_{24} + g(4, \{3\})\} \\ &= \min \{9 + g(3, \{4\}), 10 + g(4, \{3\})\} \end{aligned}$$

$$g(3, \{4\}) = \min \{c_{34} + g(4, \Phi)\} = 12 + 8 = 20$$

$$g(4, \{3\}) = \min \{c_{43} + g(3, \Phi)\} = 9 + 6 = 15$$

$$\text{Therefore, } g(2, \{3, 4\}) = \min \{9 + 20, 10 + 15\} = \min \{29, 25\} = 25$$

$$g(3, \{2, 4\}) = \min \{(c_{32} + g(2, \{4\})), (c_{34} + g(4, \{2\}))\}$$

$$g(2, \{4\}) = \min \{c_{24} + g(4, \Phi)\} = 10 + 8 = 18$$

$$g(4, \{2\}) = \min \{c_{42} + g(2, \Phi)\} = 8 + 5 = 13$$

$$\text{Therefore, } g(3, \{2, 4\}) = \min \{13 + 18, 12 + 13\} = \min \{41, 25\} = 25$$

$$g(4, \{2, 3\}) = \min \{c_{42} + g(2, \{3\}), c_{43} + g(3, \{2\})\}$$

$$g(2, \{3\}) = \min \{c_{23} + g(3, \Phi)\} = 9 + 6 = 15$$

$$g(3, \{2\}) = \min \{c_{32} + g(2, \Phi)\} = 13 + 5 = 18$$

$$\text{Therefore, } g(4, \{2, 3\}) = \min \{8 + 15, 9 + 18\} = \min \{23, 27\} = 23$$

$$\begin{aligned} g(1, \{2, 3, 4\}) &= \min \{c_{12} + g(2, \{3, 4\}), c_{13} + g(3, \{2, 4\}), c_{14} + g(4, \{2, 3\})\} \\ &= \min \{10 + 25, 15 + 25, 20 + 23\} = \min \{35, 40, 43\} = 35 \end{aligned}$$

The optimal tour for the graph has length = 35

The optimal tour is: 1, 2, 4, 3, 1.

## 0/1 – KNAPSACK:

We are given  $n$  objects and a knapsack. Each object  $i$  has a positive weight  $w_i$  and a positive value  $V_i$ . The knapsack can carry a weight not exceeding  $W$ . Fill the knapsack so that the value of objects in the knapsack is optimized.

A solution to the knapsack problem can be obtained by making a sequence of decisions on the variables  $x_1, x_2, \dots, x_n$ . A decision on variable  $x_i$  involves determining which of the values 0 or 1 is to be assigned to it. Let us assume that

decisions on the  $x_i$  are made in the order  $x_n, x_{n-1}, \dots, x_1$ . Following a decision on  $x_n$ , we may be in one of two possible states: the capacity remaining in  $m - w_n$  and a profit of  $p_n$  has accrued. It is clear that the remaining decisions  $x_{n-1}, \dots, x_1$  must be optimal with respect to the problem state resulting from the decision on  $x_n$ . Otherwise,  $x_n, \dots, x_1$  will not be optimal. Hence, the principle of optimality holds.

$$F_n(m) = \max \{f_{n-1}(m), f_{n-1}(m - w_n) + p_n\} \quad -- \quad 1$$

For arbitrary  $f_i(y)$ ,  $i > 0$ , this equation generalizes to:

$$F_i(y) = \max \{f_{i-1}(y), f_{i-1}(y - w_i) + p_i\} \quad -- \quad 2$$

Equation-2 can be solved for  $F_n(m)$  by beginning with the knowledge  $f_0(y) = 0$  for all  $y$  and  $f_i(y) = -\infty$ ,  $y < 0$ . Then  $f_1, f_2, \dots, f_n$  can be successively computed using equation-2.

When the  $w_i$ 's are integer, we need to compute  $f_i(y)$  for integer  $y$ ,  $0 \leq y \leq m$ . Since  $f_i(y) = -\infty$  for  $y < 0$ , these function values need not be computed explicitly. Since each  $f_i$  can be computed from  $f_{i-1}$  in  $\Theta(m)$  time, it takes  $\Theta(mn)$  time to compute  $f_n$ . When the  $w_i$ 's are real numbers,  $f_i(y)$  is needed for real numbers  $y$  such that  $0 \leq y \leq m$ . So,  $f_i$  cannot be explicitly computed for all  $y$  in this range. Even when the  $w_i$ 's are integer, the explicit  $\Theta(mn)$  computation of  $f_n$  may not be the most efficient computation. So, we explore **an alternative method for both cases**.

The  $f_i(y)$  is an ascending step function; i.e., there are a finite number of  $y$ 's,  $0 = y_1 < y_2 < \dots < y_k$ , such that  $f_i(y_1) < f_i(y_2) < \dots < f_i(y_k)$ ;  $f_i(y) = -\infty$ ,  $y < y_1$ ;  $f_i(y) = f_i(y_k)$ ,  $y \geq y_k$ ; and  $f_i(y) = f_i(y_j)$ ,  $y_j \leq y \leq y_{j+1}$ . So, we need to compute only  $f_i(y_j)$ ,  $1 \leq j \leq k$ . We use the ordered set  $S^i = \{(f_i(y_j), y_j) \mid 1 \leq j \leq k\}$  to represent  $f_i(y)$ . Each number of  $S^i$  is a pair  $(P, W)$ , where  $P = f_i(y_j)$  and  $W = y_j$ . Notice that  $S^0 = \{(0, 0)\}$ . We can compute  $S^{i+1}$  from  $S^i$  by first computing:

$$S^i_1 = \{(P, W) \mid (P - p_i, W - w_i) \in S^i\}$$

Now,  $S^{i+1}$  can be computed by merging the pairs in  $S^i$  and  $S^i_1$  together. Note that if  $S^{i+1}$  contains two pairs  $(P_j, W_j)$  and  $(P_k, W_k)$  with the property that  $P_j \leq P_k$  and  $W_j \geq W_k$ , then the pair  $(P_j, W_j)$  can be discarded because of equation-2. Discarding or purging rules such as this one are also known as dominance rules. Dominated tuples get purged. In the above,  $(P_k, W_k)$  dominates  $(P_j, W_j)$ .

### Example 1:

Consider the knapsack instance  $n = 3$ ,  $(w_1, w_2, w_3) = (2, 3, 4)$ ,  $(P_1, P_2, P_3) = (1, 2, 5)$  and  $M = 6$ .

**Solution:**

Initially,  $f_0(x) = 0$ , for all  $x$  and  $f_i(x) = -\infty$  if  $x < 0$ .

$$F_n(M) = \max \{f_{n-1}(M), f_{n-1}(M - w_n) + p_n\}$$

$$F_3(6) = \max \{f_2(6), f_2(6 - 4) + 5\} = \max \{f_2(6), f_2(2) + 5\}$$

$$F_2(6) = \max \{f_1(6), f_1(6 - 3) + 2\} = \max \{f_1(6), f_1(3) + 2\}$$

$$F_1(6) = \max \{f_0(6), f_0(6 - 2) + 1\} = \max \{0, 0 + 1\} = 1$$

$$F_1(3) = \max \{f_0(3), f_0(3 - 2) + 1\} = \max \{0, 0 + 1\} = 1$$

Therefore,  $F_2(6) = \max \{1, 1 + 2\} = 3$

$$F_2(2) = \max \{f_1(2), f_1(2 - 3) + 2\} = \max \{f_1(2), -\infty + 2\}$$

$$F_1(2) = \max \{f_0(2), f_0(2 - 2) + 1\} = \max \{0, 0 + 1\} = 1$$

$$F_2(2) = \max \{1, -\infty + 2\} = 1$$

Finally,  $f_3(6) = \max \{3, 1 + 5\} = 6$

**Other Solution:**

For the given data we have:

$$S^0 = \{(0, 0)\}; S^0 = \{(1, 2)\}$$

$$S^1 = (S^0 \cup S^{0_1}) = \{(0, 0), (1, 2)\}$$

$$\begin{array}{ll} X - 2 = 0 \Rightarrow x = 2. & y - 3 = 0 \Rightarrow y = 3 \\ X - 2 = 1 \Rightarrow x = 3. & y - 3 = 2 \Rightarrow y = 5 \end{array}$$

$$S^{1_1} = \{(2, 3), (3, 5)\}$$

$$S^2 = (S^1 \cup S^{1_1}) = \{(0, 0), (1, 2), (2, 3), (3, 5)\}$$

$$\begin{array}{ll} X - 5 = 0 \Rightarrow x = 5. & y - 4 = 0 \Rightarrow y = 4 \\ X - 5 = 1 \Rightarrow x = 6. & y - 4 = 2 \Rightarrow y = 6 \\ X - 5 = 2 \Rightarrow x = 7. & y - 4 = 3 \Rightarrow y = 7 \\ X - 5 = 3 \Rightarrow x = 8. & y - 4 = 5 \Rightarrow y = 9 \end{array}$$

$$S^{2_1} = \{(5, 4), (6, 6), (7, 7), (8, 9)\}$$

$$S^3 = (S^2 \cup S^{2_1}) = \{(0, 0), (1, 2), (2, 3), (3, 5), (5, 4), (6, 6), (7, 7), (8, 9)\}$$

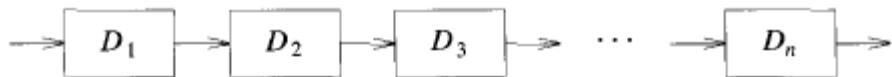
By applying Dominance rule,

$$S^3 = (S^2 \cup S^{2_1}) = \{(0, 0), (1, 2), (2, 3), (5, 4), (6, 6)\}$$

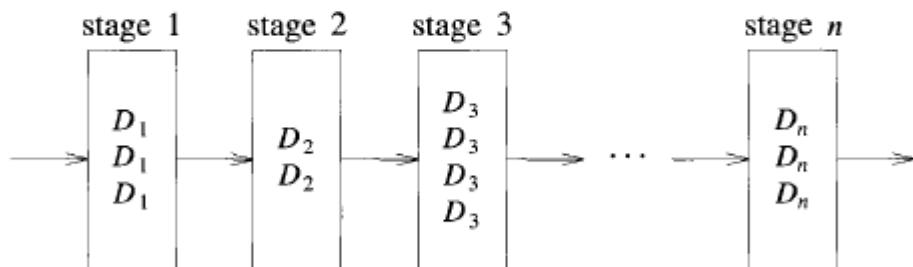
From (6, 6) we can infer that the maximum Profit  $\sum p_i x_i = 6$  and weight  $\sum x_i w_i = 6$

## Reliability Design:

The problem is to design a system that is composed of several devices connected in series. Let  $r_i$  be the reliability of device  $D_i$  (that is  $r_i$  is the probability that device  $i$  will function properly) then the reliability of the entire system is  $\prod r_i$ . Even if the individual devices are very reliable (the  $r_i$ 's are very close to one), the reliability of the system may not be very good. For example, if  $n = 10$  and  $r_i = 0.99$ ,  $i \leq i \leq 10$ , then  $\prod r_i = .904$ . Hence, it is desirable to duplicate devices. Multiply copies of the same device type are connected in parallel.



$n$  devices  $D_i$ ,  $1 \leq i \leq n$ , connected in series



Multiple devices connected in parallel in each stage

If stage  $i$  contains  $m_i$  copies of device  $D_i$ . Then the probability that all  $m_i$  have a malfunction is  $(1 - r_i)^{m_i}$ . Hence the reliability of stage  $i$  becomes  $1 - (1 - r_i)^{m_i}$ .

The reliability of stage ' $i$ ' is given by a function  $\phi_i(m_i)$ .

Our problem is to use device duplication. This maximization is to be carried out under a cost constraint. Let  $c_i$  be the cost of each unit of device  $i$  and let  $C$  be the maximum allowable cost of the system being designed.

We wish to solve:

$$\text{Maximize } \prod_{1 \leq i \leq n} \phi_i(m_i)$$

$$\text{Subject to } \sum_{1 \leq i \leq n} C_i m_i < C$$

$$m_i \geq 1 \text{ and integer, } 1 \leq i \leq n$$

Assume each  $C_i > 0$ , each  $m_i$  must be in the range  $1 \leq m_i \leq u_i$ , where

$$u_i = \left\lceil C_i + \frac{\sum_{j=1}^n C_j}{C_i} \right\rceil$$

The upper bound  $u_i$  follows from the observation that  $m_j \geq 1$

An optimal solution  $m_1, m_2, \dots, m_n$  is the result of a sequence of decisions, one decision for each  $m_i$ .

Let  $f_i(x)$  represent the maximum value of  $\max_{1 \leq j \leq i} \phi(m_j)$

Subject to the constraints:

$$\sum_{1 \leq j \leq i} C_j m_j \leq x \quad \text{and } 1 \leq m_j \leq u_j, \quad 1 \leq j \leq i$$

**Example :**

Design a three stage system with device types  $D_1$ ,  $D_2$  and  $D_3$ . The costs are \$30, \$15 and \$20 respectively. The Cost of the system is to be no more than \$105. The reliability of each device is 0.9, 0.8 and 0.5 respectively.

**Solution:**

We assume that if stage I has  $m_i$  devices of type  $i$  in parallel, then  $\phi_i(m_i) = 1 - (1 - r_i)^{m_i}$

Since, we can assume each  $c_i > 0$ , each  $m_i$  must be in the range  $1 \leq m_i \leq u_i$ . Where:

$$u_i = \left\lfloor \frac{\left( C + C_i - \sum_1^n C_j \right)}{C_i} \right\rfloor$$

Using the above equation compute  $u_1$ ,  $u_2$  and  $u_3$ ,

$$u_1 = \frac{105 + 30 - (30 + 15 + 20)}{30} = \frac{70}{30} = 2$$

$$u_2 = \frac{105 + 15 - (30 + 15 + 20)}{15} = \frac{55}{15} = 3$$

$$u_3 = \frac{105 + 20 - (30 + 15 + 20)}{20} = \frac{60}{20} = 3$$

We use  $S_j^i \rightarrow i: \text{stage number and } j: \text{no. of devices in stage } i = m_i$

$$S^o = \{f_o(x), x\} \quad \text{initially } f_o(x) = 1 \text{ and } x = 0, \text{ so, } S^o = \{1, 0\}$$

Compute  $S^1$ ,  $S^2$  and  $S^3$  as follows:

$S^1$  = depends on  $u_1$  value, as  $u_1 = 2$ , so

$$S^1 = \left\{ \begin{smallmatrix} S_1^1 \\ S_2^1 \end{smallmatrix} \right\}$$

$S^2$  = depends on  $u_2$  value, as  $u_2 = 3$ , so

$$S^2 = \left\{ \begin{matrix} S^2_1, & S^2_2, & S^2_3 \end{matrix} \right\}$$

$S^3$  = depends on  $u_3$  value, as  $u_3 = 3$ , so

$$S^3 = \left\{ \begin{matrix} S^3_1, & S^3_2, & S^3_3 \end{matrix} \right\}$$

Now find  $S^1_1 = \{(f(x), x)\}$

$f_1(x) = \{\phi_1(1) f_0(\ ), \phi_1(2) f_0(\ )\}$  With devices  $m_1 = 1$  and  $m_2 = 2$

Compute  $\phi_1(1)$  and  $\phi_1(2)$  using the formula:  $\phi_i(mi) = 1 - (1 - r_i)^{mi}$

$$\phi_1(1) = 1 - (1 - r_1)^{m_1} = 1 - (1 - 0.9)^1 = 0.9$$

$$\phi_1(2) = 1 - (1 - 0.9)^2 = 0.99$$

$$S_1 = \left\{ \begin{matrix} f_1(x), & x \end{matrix} \right\} = (0.9, 30)$$

$$S_2^1 = \{0.99, 30 + 30\} = (0.99, 60)$$

Therefore,  $S^1 = \{(0.9, 30), (0.99, 60)\}$

Next find  $S^2_1 = \{(f(x), x)\}$

$$f_2(x) = \{\phi_2(1) * f_1(\ ), \phi_2(2) * f_1(\ ), \phi_2(3) * f_1(\ )\}$$

$$\phi_2(1) = 1 - (1 - r_{I_m})_1 = 1 - (1 - 0.8) = 1 - 0.2 = 0.8$$

$$\phi_2(2) = 1 - (1 - 0.8)^2 = 0.96$$

$$\phi_2(3) = 1 - (1 - 0.8)^3 = 0.992$$

$$S_1^2 = \{(0.8(0.9), 30 + 15), (0.8(0.99), 60 + 15)\} = \{(0.72, 45), (0.792, 75)\}$$

$$\begin{aligned} S_2^2 &= \{(0.96(0.9), 30 + 15 + 15), (0.96(0.99), 60 + 15 + 15)\} \\ &= \{(0.864, 60), (0.9504, 90)\} \end{aligned}$$

$$\begin{aligned} S_3^2 &= \{(0.992(0.9), 30 + 15 + 15 + 15), (0.992(0.99), 60 + 15 + 15 + 15)\} \\ &= \{(0.8928, 75), (0.98208, 105)\} \end{aligned}$$

$$S^2 = \left\{ \begin{matrix} S^2_1, & S^2_2, & S^2_3 \end{matrix} \right\}$$

By applying Dominance rule to  $S^2$ :

Therefore,  $S^2 = \{(0.72, 45), (0.864, 60), (0.8928, 75)\}$

Dominance Rule:

If  $S^i$  contains two pairs  $(f_1, x_1)$  and  $(f_2, x_2)$  with the property that  $f_1 \geq f_2$  and  $x_1 \leq x_2$ , then  $(f_1, x_1)$  dominates  $(f_2, x_2)$ , hence by dominance rule  $(f_2, x_2)$  can be discarded. Discarding or pruning rules such as the one above is known as dominance rule. Dominating tuples will be present in  $S^i$  and Dominated tuples has to be discarded from  $S^i$ .

Case 1: if  $f_1 \leq f_2$  and  $x_1 > x_2$  then discard  $(f_1, x_1)$

Case 2: if  $f_1 \geq f_2$  and  $x_1 < x_2$  the discard  $(f_2, x_2)$

Case 3: otherwise simply write  $(f_1, x_1)$

$$S_2 = \{(0.72, 45), (0.864, 60), (0.8928, 75)\}$$

$$\phi_3(1) = 1 - (1 - r_I)^{m_i} = 1 - (1 - 0.5)^1 = 1 - 0.5 = 0.5$$

$$\phi_3(2) = 1 - (1 - 0.5)^2 = 0.75$$

$$\phi_3(3) = 1 - (1 - 0.5)^3 = 0.875$$

$$S_1^3 = \{(0.5(0.72), 45 + 20), (0.5(0.864), 60 + 20), (0.5(0.8928), 75 + 20)\}$$

$$S_1^3 = \{(0.36, 65), (0.437, 80), (0.4464, 95)\}$$

$$S_2^3 = \{(0.75(0.72), 45 + 20 + 20), (0.75(0.864), 60 + 20 + 20), \\ (0.75(0.8928), 75 + 20 + 20)\}$$

$$= \{(0.54, 85), (0.648, 100), (0.6696, 115)\}$$

$$S_3^3 = \{(0.875(0.72), 45 + 20 + 20 + 20), (0.875(0.864), 60 + 20 + 20 + 20), \\ (0.875(0.8928), 75 + 20 + 20 + 20)\}$$

$$S_3^3 = \{(0.63, 105), (1.756, 120), (0.7812, 135)\}$$

If cost exceeds 105, remove that tuples

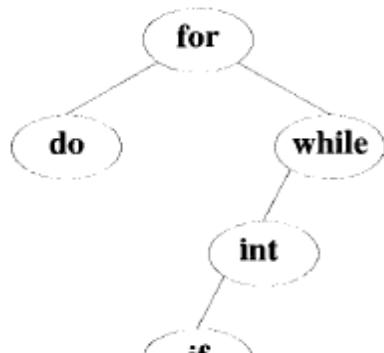
$$S^3 = \{(0.36, 65), (0.437, 80), (0.54, 85), (0.648, 100)\}$$

The best design has a reliability of 0.648 and a cost of 100. Tracing back for the solution through  $S^i$ 's we can determine that  $m_3 = 2$ ,  $m_2 = 2$  and  $m_1 = 1$ .

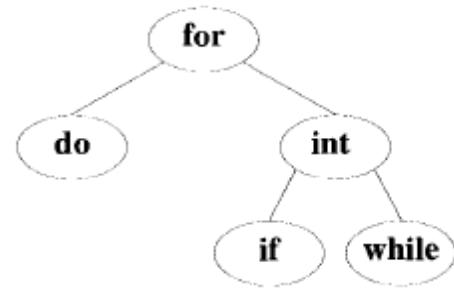
## Optimal Binary Search Tree:

In computer science, an optimal binary search tree (Optimal BST), sometimes called a weight-balanced binary tree,<sup>[1]</sup> is a binary search tree which provides the smallest possible search time (or expected search time) for a given sequence of accesses (or access probabilities).

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(a)

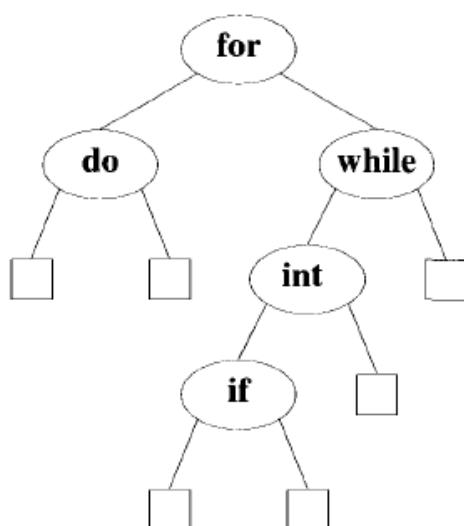


(b)

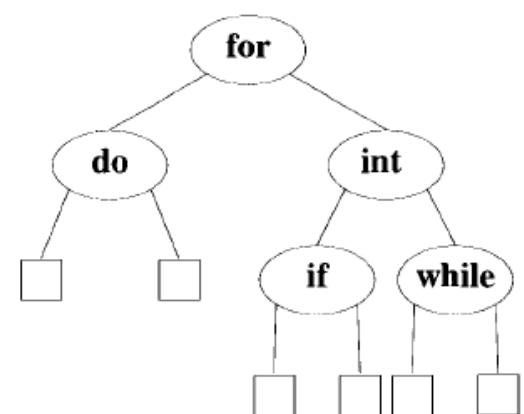
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Two possible binary search trees

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(a)

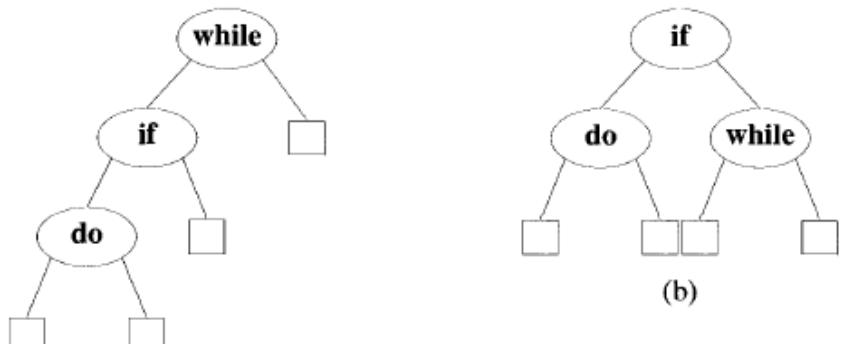


(b)

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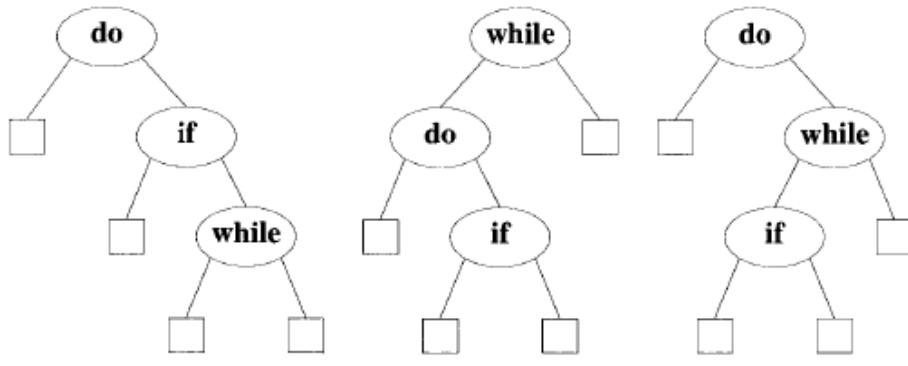
Binary search trees of Figure with external nodes added

The no of external nodes are same in both trees.



(a)

(b)



(c)

(d)

(e)

Possible binary search trees for the identifier set {**do**, **if**, **while**}

The  $C(i, J)$  can be computed as:

$$\begin{aligned} C(i, J) &= \min_{i < k \leq J} \{C(i, k-1) + C(k, J) + P(K) + w(i, K-1) + w(K, J)\} \\ &= \min_{i < k \leq J} \{C(i, K-1) + C(K, J)\} + w(i, J) \quad \text{-- (1)} \end{aligned}$$

$$\text{Where } W(i, J) = P(J) + Q(J) + w(i, J-1) \quad \text{-- (2)}$$

Initially  $C(i, i) = 0$  and  $w(i, i) = Q(i)$  for  $0 \leq i \leq n$ .

$C(i, J)$  is the cost of the optimal binary search tree ' $T_{ij}$ ' during computation we record the root  $R(i, J)$  of each tree ' $T_{ij}$ '. Then an optimal binary search tree may be constructed from these  $R(i, J)$ .  $R(i, J)$  is the value of 'K' that minimizes equation (1).

We solve the problem by knowing  $W(i, i+1)$ ,  $C(i, i+1)$  and  $R(i, i+1)$ ,  $0 \leq i < 4$ ; Knowing  $W(i, i+2)$ ,  $C(i, i+2)$  and  $R(i, i+2)$ ,  $0 \leq i < 3$  and repeating until  $W(0, n)$ ,  $C(0, n)$  and  $R(0, n)$  are obtained.

**Example** Let  $n = 4$  and  $(a_1, a_2, a_3, a_4) = (\text{do, if, int, while})$ . Let  $p(1 : 4) = (3, 3, 1, 1)$  and  $q(0 : 4) = (2, 3, 1, 1, 1)$ . The  $p$ 's and  $q$ 's have been multiplied by 16 for convenience. Initially, we have  $w(i, i) = q(i), c(i, i) = 0$  and  $r(i, i) = 0, 0 \leq i \leq 4$ . the observation  $w(i, j) = p(j) + q(j) + w(i, j - 1)$ , we get

$$\begin{aligned}
w(0, 1) &= p(1) + q(1) + w(0, 0) = 8 \\
c(0, 1) &= w(0, 1) + \min\{c(0, 0) + c(1, 1)\} = 8 \\
r(0, 1) &= 1 \\
w(1, 2) &= p(2) + q(2) + w(1, 1) = 7 \\
c(1, 2) &= w(1, 2) + \min\{c(1, 1) + c(2, 2)\} = 7 \\
r(0, 2) &= 2 \\
w(2, 3) &= p(3) + q(3) + w(2, 2) = 3 \\
c(2, 3) &= w(2, 3) + \min\{c(2, 2) + c(3, 3)\} = 3 \\
r(2, 3) &= 3 \\
w(3, 4) &= p(4) + q(4) + w(3, 3) = 3 \\
c(3, 4) &= w(3, 4) + \min\{c(3, 3) + c(4, 4)\} = 3 \\
r(3, 4) &= 4
\end{aligned}$$

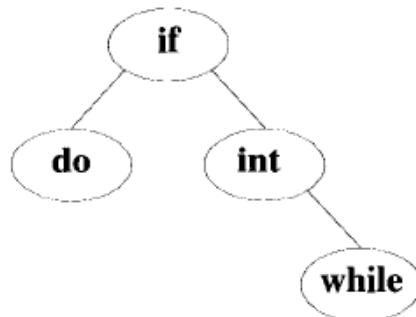
Knowing  $w(i, i + 1)$  and  $c(i, i + 1)$ ,  $0 \leq i < 4$ , we can again use Equation 5.12 to compute  $w(i, i + 2)$ ,  $c(i, i + 2)$ , and  $r(i, i + 2)$ ,  $0 \leq i < 3$ . This process can be repeated until  $w(0, 4)$ ,  $c(0, 4)$ , and  $r(0, 4)$  are obtained.

---

	0	1	2	3	4
0	$w_{00} = 2$ $c_{00} = 0$ $r_{00} = 0$	$w_{11} = 3$ $c_{11} = 0$ $r_{11} = 0$	$w_{22} = 1$ $c_{22} = 0$ $r_{22} = 0$	$w_{33} = 1$ $c_{33} = 0$ $r_{33} = 0$	$w_{44} = 1$ $c_{44} = 0$ $r_{44} = 0$
1	$w_{01} = 8$ $c_{01} = 8$ $r_{01} = 1$	$w_{12} = 7$ $c_{12} = 7$ $r_{12} = 2$	$w_{23} = 3$ $c_{23} = 3$ $r_{23} = 3$	$w_{34} = 3$ $c_{34} = 3$ $r_{34} = 4$	
2	$w_{02} = 12$ $c_{02} = 19$ $r_{02} = 1$	$w_{13} = 9$ $c_{13} = 12$ $r_{13} = 2$		$w_{24} = 5$ $c_{24} = 8$ $r_{24} = 3$	
3	$w_{03} = 14$ $c_{03} = 25$ $r_{03} = 2$	$w_{14} = 11$ $c_{14} = 19$ $r_{14} = 2$			
4	$w_{04} = 16$ $c_{04} = 32$ $r_{04} = 2$				

---

Computation of  $c(0, 4)$ ,  $w(0, 4)$ , and  $r(0, 4)$



Optimal search tree for Example



# Matrix chain multiplication

## The problem

Given a sequence of matrices  $A_1, A_2, A_3, \dots, A_n$ , find the best way (using the minimal number of multiplications) to compute their product.

- Isn't there only one way?  $((\cdots((A_1 \cdot A_2) \cdot A_3) \cdots) \cdot A_n)$
- No, matrix multiplication is *associative*.  
e.g.  $A_1 \cdot (A_2 \cdot (A_3 \cdot (\cdots(A_{n-1} \cdot A_n) \cdots)))$  yields the same matrix.
- Different multiplication orders do not cost the same:
  - Multiplying  $p \times q$  matrix  $A$  and  $q \times r$  matrix  $B$  takes  $p \cdot q \cdot r$  multiplications; result is a  $p \times r$  matrix.
  - Consider multiplying  $10 \times 100$  matrix  $A_1$  with  $100 \times 5$  matrix  $A_2$  and  $5 \times 50$  matrix  $A_3$ .
    - $(A_1 \cdot A_2) \cdot A_3$  takes  $10 \cdot 100 \cdot 5 + 10 \cdot 5 \cdot 50 = 7500$  multiplications.
    - $A_1 \cdot (A_2 \cdot A_3)$  takes  $100 \cdot 5 \cdot 50 + 10 \cdot 50 \cdot 100 = 75000$  multiplications.

## Notation

- In general, let  $A_i$  be  $p_{i-1} \times p_i$  matrix.
- Let  $m(i, j)$  denote minimal number of multiplications needed to compute  $A_i \cdot A_{i+1} \cdots A_j$
- We want to compute  $m(1, n)$ .

## Recursive algorithm

- Assume that someone tells us the position of the **last** product, say  $k$ . Then we have to compute recursively the best way to multiply the chain from  $i$  to  $k$ , and from  $k + 1$  to  $j$ , and add the cost of the final product. This means that

$$m(i, j) = m(i, k) + m(k + 1, j) + p_{i-1} \cdot p_k \cdot p_j$$

- If noone tells us  $k$ , then we have to try all possible values of  $k$  and pick the best solution.
- Recursive formulation of  $m(i, j)$ :

$$m(i, j) = \begin{cases} 0 & \text{If } i = j \\ \min_{i \leq k < j} \{m(i, k) + m(k + 1, j) + p_{i-1} \cdot p_k \cdot p_j\} & \text{If } i < j \end{cases}$$

- To go from the recursive formulation above to a program is pretty straightforward:

```

Matrix-chain(i, j)
  IF i = j THEN return 0
  m =  $\infty$ 
  FOR k = i TO j - 1 DO
    q = Matrix-chain(i, k) + Matrix-chain(k + 1, j) +  $p_{i-1} \cdot p_k \cdot p_j$ 
    IF q < m THEN m = q
  OD
  Return m
END Matrix-chain

Return Matrix-chain(1, n)

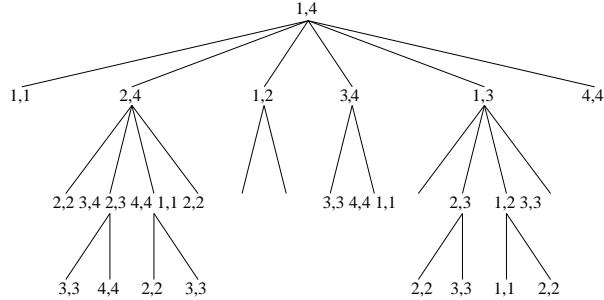
```

- Running time:

$$\begin{aligned}
T(n) &= \sum_{k=1}^{n-1} (T(k) + T(n-k) + O(1)) \\
&= 2 \cdot \sum_{k=1}^{n-1} T(k) + O(n) \\
&\geq 2 \cdot T(n-1) \\
&\geq 2 \cdot 2 \cdot T(n-2) \\
&\geq 2 \cdot 2 \cdot 2 \dots \\
&= 2^n
\end{aligned}$$

- Exponential is ... SLOW!
- Problem is that we compute the same result over and over again.

– Example: Recursion tree for Matrix-chain(1, 4)



For example, we compute Matrix-chain(3, 4) twice.

## Dynamic programming with a table and recursion

- Solution is to “remember” the values we have already computed in a table. This is called *memoization*. We’ll have a table  $T[1..n][1..n]$  such that  $T[i][j]$  stores the solution to problem Matrix-CHAIN(i,j). Initially all entries will be set to  $\infty$ .

```

FOR  $i = 1$  to  $n$  DO
    FOR  $j = i$  to  $n$  DO
         $T[i][j] = \infty$ 
    OD
OD

```

- The code for MATRIX-CHAIN(i,j) stays the same, except that it now uses the table. The first thing MATRIX-CHAIN(i,j) does is to check the table to see if  $T[i][j]$  is already computed. If so, it returns it, otherwise, it computes it and writes it in the table. Below is the updated code.

```

Matrix-chain( $i, j$ )
    IF  $T[i][j] < \infty$  THEN return  $T[i][j]$ 
    IF  $i = j$  THEN  $T[i][j] = 0$ , return 0
     $m = \infty$ 
    FOR  $k = i$  to  $j - 1$  DO
         $q = \text{Matrix-chain}(i, k) + \text{Matrix-chain}(k + 1, j) + p_{i-1} \cdot p_k \cdot p_j$ 
        IF  $q < m$  THEN  $m = q$ 
    OD
     $T[i][j] = m$ 
    return  $m$ 
END Matrix-chain

return Matrix-chain(1,  $n$ )

```

- The table will prevent a subproblem MATRIX-CHAIN(i,j) to be computed more than once.
- Running time:
  - $\Theta(n^2)$  different calls to matrix-chain( $i, j$ ).
  - The first time a call is made it takes  $O(n)$  time, *not* counting recursive calls.
  - When a call has been made once it costs  $O(1)$  time to make it again.  
 $\Downarrow$   
 $O(n^3)$  time
  - Another way of thinking about it:  $\Theta(n^2)$  total entries to fill, it takes  $O(n)$  to fill one.

**UNIT IV:**

**Graph traversals** - Breadth first search and Depth first search, AND / OR graphs, game trees, Connected Components, Bi - connected components.

**Backtracking:** General method, applications-n-queen problem, sum of subsets problem, graph coloring, Hamiltonian cycles.

## Graph traversals

Given a graph  $G = (V, E)$  and a vertex  $V$  in  $V(G)$  traversing can be done in two ways.

1. Depth first search
2. Breadth first search

**Depth first search:**

With depth first search, the start state is chosen to begin, then some successor of the start state, then some successor of that state, then some successor of that and so on, trying to reach a goal state.

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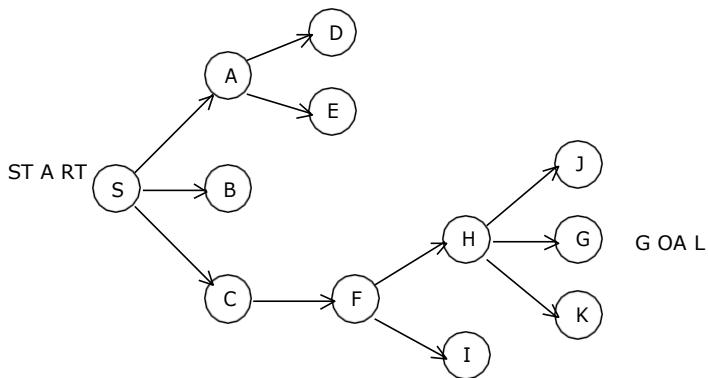
```
1  Algorithm BFS( $v$ )
2  // A breadth first search of  $G$  is carried out beginning
3  // at vertex  $v$ . For any node  $i$ ,  $visited[i] = 1$  if  $i$  has
4  // already been visited. The graph  $G$  and array  $visited[ ]$ 
5  // are global;  $visited[ ]$  is initialized to zero.
6  {
7       $u := v$ ; //  $q$  is a queue of unexplored vertices.
8       $visited[v] := 1$ ;
9      repeat
10     {
11         for all vertices  $w$  adjacent from  $u$  do
12             {
13                 if ( $visited[w] = 0$ ) then
14                     {
15                         Add  $w$  to  $q$ ; //  $w$  is unexplored.
16                          $visited[w] := 1$ ;
17                     }
18             }
19             if  $q$  is empty return; // No unexplored vertex.
20             Delete  $u$  from  $q$ ; // Get first unexplored vertex.
21     } until( $false$ );
22 }
```

---

Pseudocode for breadth first search

If depth first search reaches a state  $S$  without successors, or if all the successors of a state  $S$  have been chosen (visited) and a goal state has not get been found, then it "backs up" that means it goes to the immediately previous state or predecessor formally, the state whose successor was 'S' originally.

For example consider the figure. The circled letters are state and arrows are branches.



Suppose S is the start and G is the only goal state. Depth first search will first visit S, then A then D. But D has no successors, so we must back up to A and try its second successor, E. But this doesn't have any successors either, so we back up to A again. But now we have tried all the successors of A and haven't found the goal state G so we must back to 'S'. Now 'S' has a second successor, B. But B has no successors, so we back up to S again and choose its third successor, C. C has one successor, F. The first successor of F is H, and the first of H is J. J doesn't have any successors, so we back up to H and try its second successor. And that's G, the only goal state. So the solution path to the goal is S, C, F, H and G and the states considered were in order S, A, D, E, B, C, F, H, J, G.

#### *Disadvantages:*

1. It works very fine when search graphs are trees or lattices, but can get stuck in an infinite loop on graphs. This is because depth first search can travel around a cycle in the graph forever.

To eliminate this keep a list of states previously visited, and never permit search to return to any of them.

2. One more problem is that, the state space tree may be of infinite depth, to prevent consideration of paths that are too long, a maximum is often placed on the depth of nodes to be expanded, and any node at that depth is treated as if it had no successors.
3. We cannot come up with shortest solution to the problem.

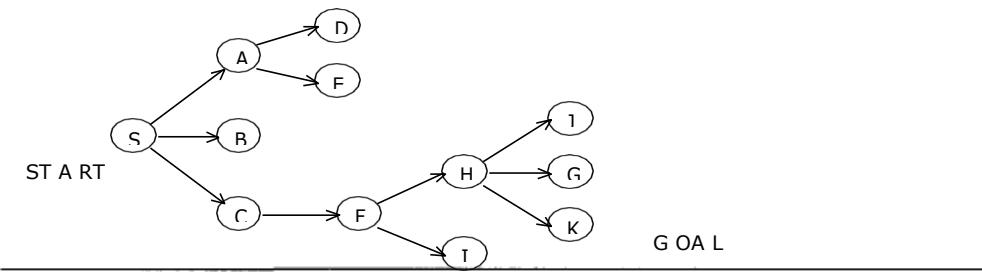
#### **Time Complexity:**

Let  $n = |V|$  and  $e = |E|$ . Observe that the initialization portion requires  $\Phi(n)$  time. Since we never visit a vertex twice, the number of times we go through the loop is at most  $n$  (exactly  $n$  assuming each vertex is reachable from the source). As, each vertex is visited at most once. At each vertex visited, we scan its adjacency list once. Thus, each edge is examined at most twice (once at each endpoint). So the total running time is  $O(n + e)$ .

#### **Breadth first search:**

Given an graph  $G = (V, E)$ , breadth-first search starts at some source vertex S and "discovers" which vertices are reachable from S. Define the distance between a vertex V and S to be the minimum number of edges on a path from S to V. Breadth-first search discovers vertices in increasing order of distance, and hence can be used as an algorithm for computing shortest paths (where the length of a path = number of edges on the path). Breadth-first search is named because it visits vertices across the entire breadth.

To illustrate this let us consider the following tree:




---

```

1 Algorithm DFS( $v$ )
2 // Given an undirected (directed) graph  $G = (V, E)$  with
3 //  $n$  vertices and an array  $visited[]$  initially set
4 // to zero, this algorithm visits all vertices
5 // reachable from  $v$ .  $G$  and  $visited[]$  are global.
6 {
7      $visited[v] := 1$ ;
8     for each vertex  $w$  adjacent from  $v$  do
9     {
10         if ( $visited[w] = 0$ ) then DFS( $w$ );
11     }
12 }

```

---

### Depth first search of a graph

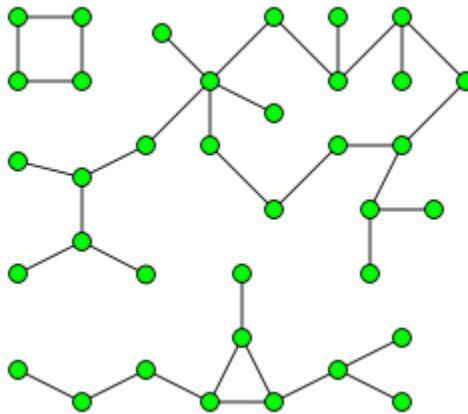
Breadth first search finds states level by level. Here we first check all the immediate successors of the start state. Then all the immediate successors of these, then all the immediate successors of these, and so on until we find a goal node. Suppose S is the start state and G is the goal state. In the figure, start state S is at level 0; A, B and C are at level 1; D, E and F at level 2; H and I at level 3; and J, G and K at level 4. So breadth first search, will consider in order S, A, B, C, D, E, F, H, I, J and G and then stop because it has reached the goal node.

Breadth first search does not have the danger of infinite loops as we consider states in order of increasing number of branches (level) from the start state.

One simple way to implement breadth first search is to use a queue data structure consisting of just a start state. Any time we need a new state, we pick it from the front of the queue and any time we find successors, we put them at the end of the queue. That way we are guaranteed to not try (find successors of) any states at level 'N' until all states at level 'N - 1' have been tried.

## Connected components

In graph theory, a connected component (or just component) of an undirected graph is a subgraph in which any two vertices are connected to each other by paths, and which is connected to no additional vertices in the super graph. For example, the graph shown in the illustration has three connected components. A vertex with no incident edges is itself a connected component. A graph that is itself connected has exactly one connected component, consisting of the whole graph.



A graph with three connected components.

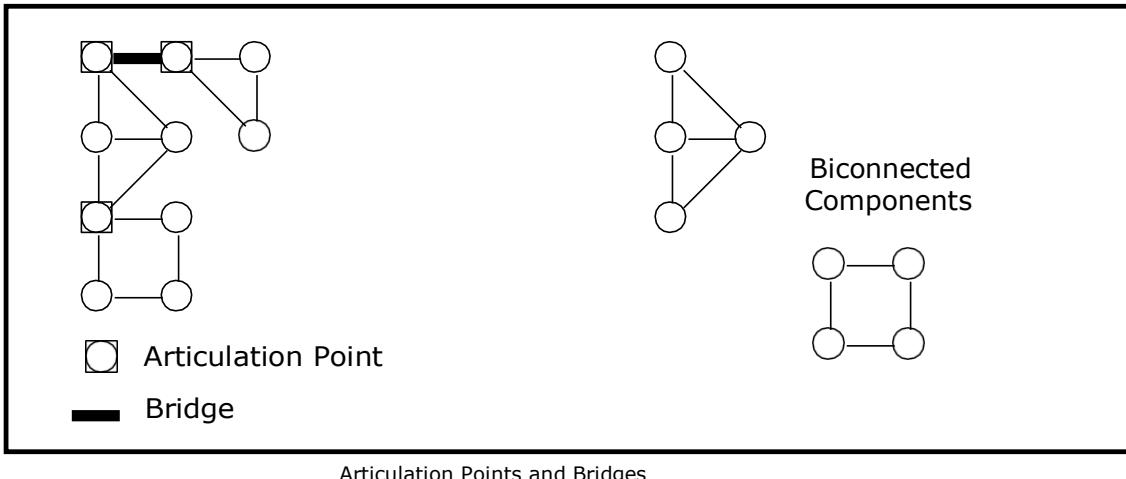
## Biconnected Components:

Let  $G = (V, E)$  be a connected undirected graph. Consider the following definitions:

**Articulation Point (or Cut Vertex):** An articulation point in a connected graph is a vertex (together with the removal of any incident edges) that, if deleted, would break the graph into two or more pieces..

**Bridge:** Is an edge whose removal results in a disconnected graph.

**Biconnected:** A graph is biconnected if it contains no articulation points. In a biconnected graph, two distinct paths connect each pair of vertices. A graph that is not biconnected divides into biconnected components. This is illustrated in the following figure:



Biconnected graphs and articulation points are of great interest in the design of network algorithms, because these are the "critical" points, whose failure will result in the network becoming disconnected.

Let us consider the typical case of vertex  $v$ , where  $v$  is not a leaf and  $v$  is not the root. Let  $w_1, w_2, \dots, w_k$  be the children of  $v$ . For each child there is a subtree of the DFS tree rooted at this child. If for some child, there is no back edge going to a proper ancestor of  $v$ , then if we remove  $v$ , this subtree becomes disconnected from the rest of the graph, and hence  $v$  is an articulation point.

$$L(u) = \min \{DFN(u), \min \{L(w) \mid w \text{ is a child of } u\}, \min \{DFN(w) \mid (u, w) \text{ is a back edge}\}\}.$$

$L(u)$  is the lowest depth first number that can be reached from ' $u$ ' using a path of descendants followed by at most one back edge. It follows that, If ' $u$ ' is not the root then ' $u$ ' is an articulation point iff ' $u$ ' has a child ' $w$ ' such that:

$$L(w) \geq DFN(u)$$

### Algorithm for finding the Articulation points:

Pseudocode to compute DFN and L.

#### Algorithm Art ( $u, v$ )

```
// u is a start vertex for depth first search. V is its parent if any in the depth first
// spanning tree. It is assumed that the global array dfn is initialized to zero and
// that // the global variable num is initialized to 1. n is the number of vertices in G.
{
```

```
dfn [u] := num; L [u] := num; num
:= num + 1; for each vertex w
adjacent from u do
{
    if (dfn [w] = 0) then
    {
        Art (w, u); // w
```

```

        is unvisited. L [u] := min (L [u], L
        [w]);
    }
    else if (w ≠ v) then L [u] := min (L [u], dfn [w]);
}
}

```

### Algorithm for finding the Biconnected Components:

#### Algorithm BiComp (u, v)

```

// u is a start vertex for depth first search. V is its parent if any in the depth first
// spanning tree. It is assumed that the global array dfn is initially zero and that the
// global variable num is initialized to 1. n is the number of vertices in G.
{

```

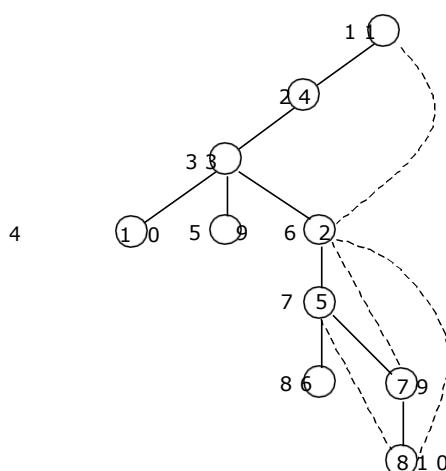
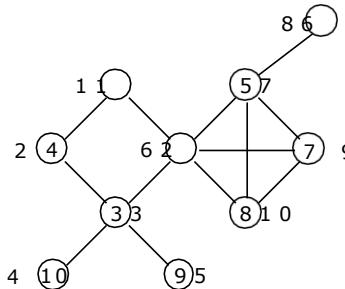
```

    dfn [u] := num; L [u] := num; num
    := num + 1; for each vertex w
    adjacent from u do
    {
        if ((v ≠ w) and (dfn [w] ≤ dfn
            [u])) then add (u, w)
            to the top of a stack
            s;
        if (dfn [w] = 0) then
        {
            if (L [w] ≥ dfn [u]) then
            {
                write ("New
                    biconponent");
                repeat
                {
                    Delete an edge from the
                    top of stack s; Let this
                    edge be (x, y);
                    Write (x, y);
                } until (((x, y) = (u, w)) or ((x, y) = (w, u)));
            }
            BiComp (w, u); // w is unvisited. L [u] := min (L [u], L [w]);
        }
        else if (w ≠ v) then L [u] := min (L [u], dfn [w]);
    }
}

```

#### Example:

For the following graph identify the articulation points and Biconnected components:



## Grap h

## Dept h Fi rst Sp an ni ng Tree

To identify the articulation points, we use:

$L(u) = \min \{DFN(u), \min \{L(w) \mid w \text{ is a child of } u\}, \min \{DFN(w) \mid w \text{ is a vertex to which there is back edge from } u\}\}$

$$L(1) = \min \{DFN(1), \min \{L(4)\}\} = \min \{1, L(4)\} = \min \{1, 1\} = 1$$

$$L(4) = \min \{DFN(4), \min \{L(3)\}\} = \min \{2, L(3)\} = \min \{2, 1\} = 1$$

$$\begin{aligned} L(3) &= \min \{DFN(3), \min \{L(10), L(9), L(2)\}\} = \\ &= \min \{3, \min \{L(10), L(9), L(2)\}\} = \min \{3, \min \{4, 5, 1\}\} = 1 \end{aligned}$$

$$L(10) = \min \{DFN(10)\} = 4$$

$$L(9) = \min \{DFN(9)\} = 5$$

$$\begin{aligned} L(2) &= \min \{DFN(2), \min \{L(5)\}, \min \{DFN(1)\}\} = \\ &= \min \{6, \min \{L(5)\}, 1\} = \min \{6, 6, 1\} = 1 \end{aligned}$$

$$L(5) = \min \{DFN(5), \min \{L(6), L(7)\}\} = \min \{7, 8, 6\} = 6$$

$$L(6) = \min \{DFN(6)\} = 8$$

$$\begin{aligned} L(7) &= \min \{DFN(7), \min \{L(8), \min \{DFN(2)\}\}\} = \\ &= \min \{9, L(8), 6\} = \min \{9, 6, 6\} = 6 \end{aligned}$$

$$\begin{aligned} L(8) &= \min \{DFN(8), \min \{DFN(5), DFN(2)\}\} = \\ &= \min \{10, \min \{7, 6\}\} = \min \{10, 6\} = 6 \end{aligned}$$

Therefore,  $L(1: 10) = (1, 1, 1, 1, 6, 8, 6, 6, 5, 4)$

### Finding the Articulation Points:

Vertex 1: Vertex 1 is not an articulation point. It is a root node. Root is an articulation point if it has two or more child nodes.

Vertex 2: is an articulation point as child 5 has  $L(5) = 6$  and  $DFN(2) = 6$ , So, the condition  $L(5) = DFN(2)$  is true.

Vertex 3: is an articulation point as child 10 has  $L(10) = 4$  and  $DFN(3) = 3$ , So, the condition  $L(10) > DFN(3)$  is true.

Vertex 4: is not an articulation point as child 3 has  $L(3) = 1$  and  $DFN(4) = 2$ , So, the condition  $L(3) \geq DFN(4)$  is false.

Vertex 5: is an articulation point as child 6 has  $L(6) = 8$ , and  $DFN(5) = 7$ , So, the condition  $L(6) > DFN(5)$  is true.

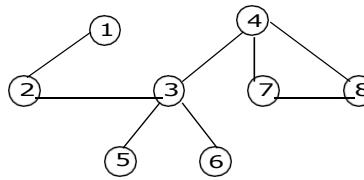
Vertex 7: is not an articulation point as child 8 has  $L(8) = 6$ , and  $DFN(7) = 9$ , So, the condition  $L(8) \geq DFN(7)$  is false.

Vertex 6, Vertex 8, Vertex 9 and Vertex 10 are leaf nodes.

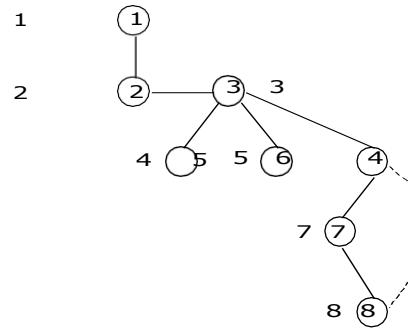
Therefore, the articulation points are  $\{2, 3, 5\}$ .

### Example:

For the following graph identify the articulation points and Biconnected components:



**G r a p h**



**D F S s p a n n i n g T r e e**

$L(u) = \min \{DFN(u), \min \{L(w) \mid w \text{ is a child of } u\}, \min \{DFN(w) \mid w \text{ is a vertex to which there is back edge from } u\}\}$

$$L(1) = \min \{DFN(1), \min \{L(2)\}\} = \min \{1, L(2)\} = \min \{1, 2\} = 1$$

$$L(2) = \min \{DFN(2), \min \{L(3)\}\} = \min \{2, L(3)\} = \min \{2, 3\} = 2$$

$$L(3) = \min \{DFN(3), \min \{L(4), L(5), L(6)\}\} = \min \{3, \min \{6, 4, 5\}\} = 3$$

$$L(4) = \min \{DFN(4), \min \{L(7)\}\} = \min \{6, L(7)\} = \min \{6, 6\} = 6$$

$$L(5) = \min \{DFN(5)\} = 4$$

$$L(6) = \min \{DFN(6)\} = 5$$

$$L(7) = \min \{DFN(7), \min \{L(8)\}\} = \min \{7, 6\} = 6$$

$$L(8) = \min \{DFN(8), \min \{DFN(4)\}\} = \min \{8, 6\} = 6$$

Therefore,  $L(1:8) = \{1, 2, 3, 6, 4, 5, 6, 6\}$

### Finding the Articulation Points:

Check for the condition if  $L(w) \geq DFN(u)$  is true, where  $w$  is any

child of  $u$ . Vertex 1: Vertex 1 is not an articulation point.

It is a root node. Root is an articulation point if it has two or more

child nodes.

Vertex 2: is an articulation point as  $L(3) = 3$  and  $DFN(2) = 2$ .  
So, the condition is true

Vertex 3: is an articulation Point as:

- I.  $L(5) = 4$  and  $DFN(3) = 3$
- II.  $L(6) = 5$  and  $DFN(3) = 3$  and
- III.  $L(4) = 6$  and

$DFN(3) = 3$  So, the

condition true in above

cases

Vertex 4: is an articulation point as  $L(7) = 6$  and  $DFN(4) = 6$ .  
So, the condition is true

Vertex 7: is not an articulation point as  $L(8) = 6$  and  $DFN(7) = 7$ .  
So, the condition is False

Vertex 5, Vertex 6 and Vertex 8 are leaf

nodes. Therefore, the articulation points

are  $\{2, 3, 4\}$ .

# BACKTRACKING

## General Method:

Backtracking is used to solve problem in which a sequence of objects is chosen from a specified set so that the sequence satisfies some criterion. The desired solution is expressed as an n-tuple  $(x_1, \dots, x_n)$  where each  $x_i \in S$ ,  $S$  being a finite set.

The solution is based on finding one or more vectors that maximize, minimize, or satisfy a criterion function  $P(x_1, \dots, x_n)$ . Form a solution and check at every step if this has any chance of success. If the solution at any point seems not promising, ignore it. All solutions require a set of constraints divided into two categories: explicit and implicit constraints.

**Definition 1:** Explicit constraints are rules that restrict each  $x_i$  to take on values only from a given set. Explicit constraints depend on the particular instance  $I$  of problem being solved. All tuples that satisfy the explicit constraints define a possible solution space for  $I$ .

**Definition 2:** Implicit constraints are rules that determine which of the tuples in the solution space of  $I$  satisfy the criterion function. Thus, implicit constraints describe the way in which the  $x_i$ 's must relate to each other.

- For 8-queens problem:

Explicit constraints using 8-tuple formation, for this problem are  $S = \{1, 2, 3, 4, 5, 6, 7, 8\}$ .

The implicit constraints for this problem are that no two queens can be the same (i.e., all queens must be on different columns) and no two queens can be on the same diagonal.

Backtracking is a modified depth first search of a tree. Backtracking algorithms determine problem solutions by systematically searching the solution space for the given problem instance. This search is facilitated by using a tree organization for the solution space.

Backtracking is the procedure whereby, after determining that a node can lead to nothing but dead end, we go back (backtrack) to the node's parent and proceed with the search on the next child.

A backtracking algorithm need not actually create a tree. Rather, it only needs to keep track of the values in the current branch being investigated. This is the way we implement backtracking algorithm. We say that the state space tree exists implicitly in the algorithm because it is not actually constructed.

**State space** is the set of paths from root node to other nodes. *State space tree* is the tree organization of the solution space. The state space trees are called static trees. This terminology follows from the observation that the tree organizations are independent of the problem instance being solved. For some problems it is advantageous to use different tree organizations for different problem instances. In this case the tree organization is determined dynamically as the solution space is being searched. Tree organizations that are problem instance dependent are called dynamic trees.

## **Terminology:**

**Problem state** is each node in the depth first search tree.

**Solution states** are the problem states 'S' for which the path from the root node to 'S' defines a tuple in the solution space.

**Answer states** are those solution states for which the path from root node to s defines a tuple that is a member of the set of solutions.

**Live node** is a node that has been generated but whose children have not yet been generated.

**E-node** is a live node whose children are currently being explored. In other words, an E-node is a node currently being expanded.

**Dead node** is a generated node that is not to be expanded or explored any further. All children of a dead node have already been expanded.

**Branch and Bound** refers to all state space search methods in which all children of an E-node are generated before any other live node can become the E-node.

Depth first node generation with bounding functions is called **backtracking**. State generation methods in which the E-node remains the E-node until it is dead, lead to branch and bound methods.

## **N-Queens Problem:**

Let us consider, N = 8. Then 8-Queens Problem is to place eight queens on an 8 x 8 chessboard so that no two "attack", that is, no two of them are on the same row, column, or diagonal.

All solutions to the 8-queens problem can be represented as 8-tuples  $(x_1, \dots, x_8)$ , where  $x_i$  is the column of the  $i^{\text{th}}$  row where the  $i^{\text{th}}$  queen is placed.

The explicit constraints using this formulation are  $S_i = \{1, 2, 3, 4, 5, 6, 7, 8\}$ ,  $1 \leq i \leq 8$ . Therefore the solution space consists of  $8^8$  8-tuples.

The implicit constraints for this problem are that no two  $x_i$ 's can be the same (i.e., all queens must be on different columns) and no two queens can be on the same diagonal.

This realization reduces the size of the solution space from  $8^8$  tuples to  $8!$  Tuples.

The promising function must check whether two queens are in the same column or diagonal:

Suppose two queens are placed at positions  $(i, j)$  and  $(k, l)$  Then:

- Column Conflicts: Two queens conflict if their  $x_i$  values are identical.
- Diag 45° conflict: Two queens  $i$  and  $j$  are on the same  $45^{\circ}$  diagonal if:

$$i - j = k - l.$$

This implies,  $j - l = i - k$

- Diag 135° conflict:  
 $i + j = k + l.$

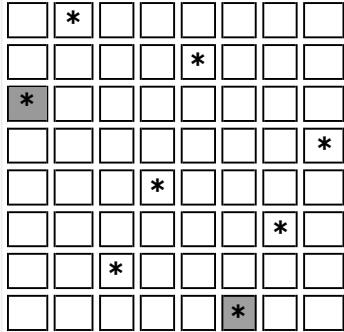
This implies,  $j - l = k - i$

Therefore, two queens lie on the same diagonal if and only if:

$$|j - l| = |i - k|$$

Where,  $j$  be the column of object in row  $i$  for the  $i^{\text{th}}$  queen and  $l$  be the column of object in row ' $k$ ' for the  $k^{\text{th}}$  queen.

To check the diagonal clashes, let us take the following tile configuration:



In this example, we have:

i	1	2	3	4	5	6	7	8
$x_i$	2	5	1	8	4	7	3	6

case whether the queens on  
are conflicting or not. In this

Let us consider for the  
3<sup>rd</sup> row and 8<sup>th</sup> row

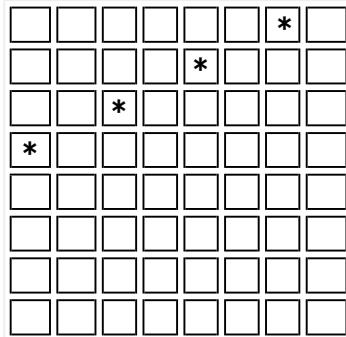
case  $(i, j) = (3, 1)$  and  $(k, l) = (8, 6)$ . Therefore:

$$|j - l| = |i - k| \Rightarrow |1 - 6| = |3 - 8| \\ \Rightarrow 5 = 5$$

In the above example we have,  $|j - l| = |i - k|$ , so the two queens are attacking.  
This is not a solution.

### Example:

Suppose we start with the feasible sequence 7, 5, 3, 1.



Step 1:

Add to the sequence the next number in the sequence 1, 2, . . . , 8 not yet used.

Step 2:

If this new sequence is feasible and has length 8 then STOP with a solution. If the new sequence is feasible and has length less than 8, repeat Step 1.

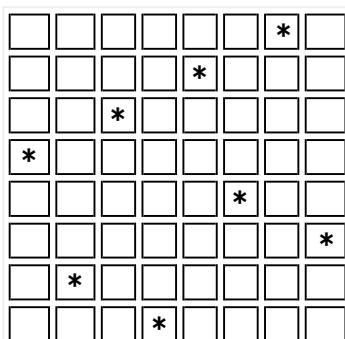
Step 3:

If the sequence is not feasible, then *backtrack* through the sequence until we find the *most recent* place at which we can exchange a value. Go back to Step 1.

<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>Remarks</b>
7	5	3	1					
7	5	3	1*	2*				$ j - l  =  1 - 2  = 1$ $ i - k  =  4 - 5  = 1$
7	5	3	1	4				
7*	5	3	1	4	2*			$ j - l  =  7 - 2  = 5$ $ i - k  =  1 - 6  = 5$
7	5	3*	1	4	6*			$ j - l  =  3 - 6  = 3$ $ i - k  =  3 - 6  = 3$
7	5	3	1	4	8			
7	5	3	1	4*	8	2*		$ j - l  =  4 - 2  = 2$ $ i - k  =  5 - 7  = 2$
7	5	3	1	4*	8	6*		$ j - l  =  4 - 6  = 2$ $ i - k  =  5 - 7  = 2$
7	5	3	1	4	8			<i>Backtrack</i>
7	5	3	1	4				<i>Backtrack</i>
7	5	3	1	6				
7*	5	3	1	6	2*			$ j - l  =  1 - 2  = 1$ $ i - k  =  7 - 6  = 1$
7	5	3	1	6	4			
7	5	3	1	6	4	2		
7	5	3*	1	6	4	2	8*	$ j - l  =  3 - 8  = 5$ $ i - k  =  3 - 8  = 5$
7	5	3	1	6	4	2		<i>Backtrack</i>
7	5	3	1	6	4			<i>Backtrack</i>
7	5	3	1	6	8			
7	5	3	1	6	8	2		
7	5	3	1	6	8	2	4	<b>SOLUTION</b>

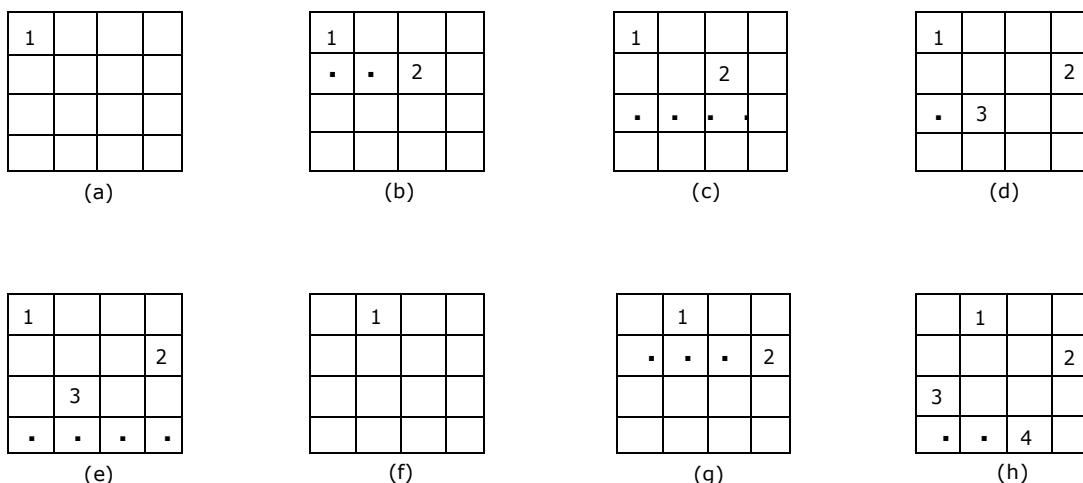
\* indicates conflicting queens.

On a chessboard, the **solution** will look like:



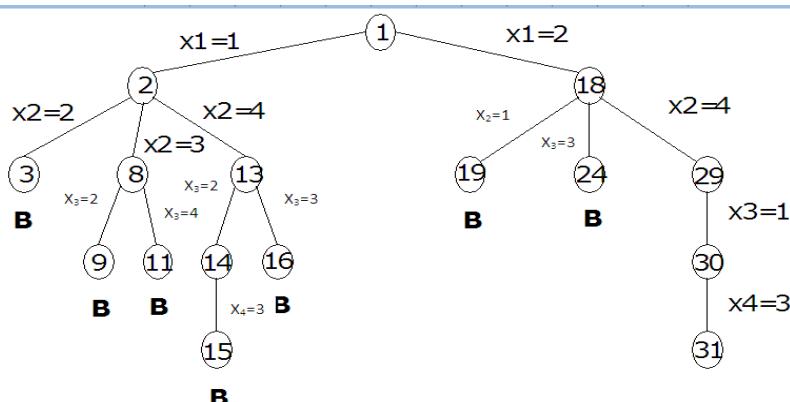
#### 4 – Queens Problem:

Let us see how backtracking works on the 4-queens problem. We start with the root node as the only live node. This becomes the E-node. We generate one child. Let us assume that the children are generated in ascending order. Let us assume that the children are generated in ascending order. Thus node number 2 of figure is generated and the path is now (1). This corresponds to placing queen 1 on column 1. Node 2 becomes the E-node. Node 3 is generated and immediately killed. The next node generated is node 8 and the path becomes (1, 3). Node 8 becomes the E-node. However, it gets killed as all its children represent board configurations that cannot lead to an answer node. We backtrack to node 2 and generate another child, node 13. The path is now (1, 4). The board configurations as backtracking proceeds is as follows:



The above figure shows graphically the steps that the backtracking algorithm goes through as it tries to find a solution. The dots indicate placements of a queen, which were tried and rejected because another queen was attacking.

In Figure (b) the second queen is placed on columns 1 and 2 and finally settles on column 3. In figure (c) the algorithm tries all four columns and is unable to place the next queen on a square. Backtracking now takes place. In figure (d) the second queen is moved to the next possible column, column 4 and the third queen is placed on column 2. The boards in Figure (e), (f), (g), and (h) show the remaining steps that the algorithm goes through until a solution is found.



Portion of the tree generated during backtracking

```

1  Algorithm Place( $k, i$ )
2  // Returns true if a queen can be placed in  $k$ th row and
3  //  $i$ th column. Otherwise it returns false.  $x[ ]$  is a
4  // global array whose first  $(k - 1)$  values have been set.
5  //  $\text{Abs}(r)$  returns the absolute value of  $r$ .
6  {
7      for  $j := 1$  to  $k - 1$  do
8          if  $((x[j] = i) \text{ or } (\text{Abs}(x[j] - i) = \text{Abs}(j - k)))$ 
9              // or in the same diagonal
10             then return false;
11
12     return true;
13 }

```

---

**Algorithm 7.4** Can a new queen be placed?

---

```

1  Algorithm NQueens( $k, n$ )
2  // Using backtracking, this procedure prints all
3  // possible placements of  $n$  queens on an  $n \times n$ 
4  // chessboard so that they are nonattacking.
5  {
6      for  $i := 1$  to  $n$  do
7      {
8          if Place( $k, i$ ) then
9          {
10              $x[k] := i;$ 
11             if  $(k = n)$  then write  $(x[1 : n])$ ;
12             else NQueens( $k + 1, n$ );
13         }
14     }
15 }

```

---

**Algorithm 7.5** All solutions to the  $n$ -queens problem

**Complexity Analysis:**

$$= \frac{n^{n+1} - 1}{n - 1}$$

$$1 + n + n^2 + n^3 + \dots + n^n$$

For the instance in which  $n = 8$ , the state space tree contains:

$$\frac{8^{8+1} - 1}{8 - 1} = 19,173,961 \text{ nodes}$$

## Sum of Subsets:

Given positive numbers  $w_i$ ,  $1 \leq i \leq n$ , and  $m$ , this problem requires finding all subsets of  $w_i$ 's whose sums are ' $m$ '.

All solutions are  $k$ -tuples,  $1 \leq k \leq n$ .

Explicit constraints:

- $x_i \in \{j \mid j \text{ is an integer and } 1 \leq j \leq n\}$ .

Implicit constraints:

- No two  $x_i$  can be the same.
- The sum of the corresponding  $w_i$ 's be  $m$ .
- $x_i < x_{i+1}$ ,  $1 \leq i < k$  (total order in indices) to avoid generating multiple instances of the same subset (for example,  $(1, 2, 4)$  and  $(1, 4, 2)$  represent the same subset).

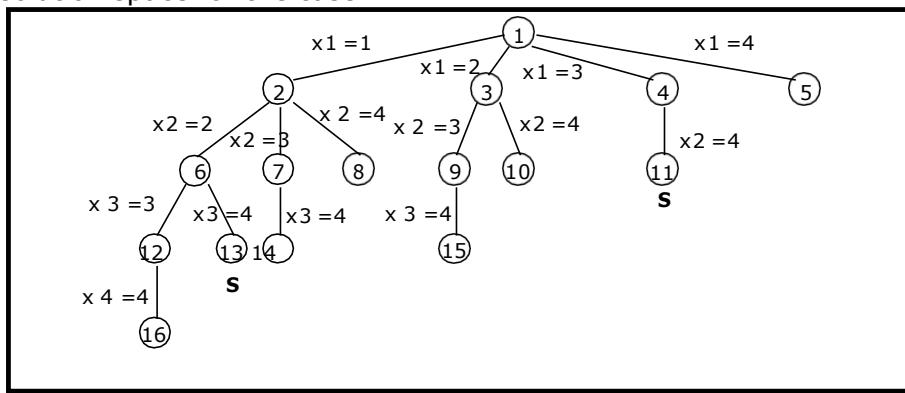
A better formulation of the problem is where the solution subset is represented by an  $n$ -tuple  $(x_1, \dots, x_n)$  such that  $x_i \in \{0, 1\}$ .

The above solutions are then represented by  $(1, 1, 0, 1)$  and  $(0, 0, 1, 1)$ .

For both the above formulations, the solution space is  $2^n$  distinct tuples.

For example,  $n = 4$ ,  $w = (11, 13, 24, 7)$  and  $m = 31$ , the desired subsets are  $(11, 13, 7)$  and  $(24, 7)$ .

The following figure shows a possible tree organization for two possible formulations of the solution space for the case  $n = 4$ .



A possible solution space organisation for the sum of the subsets problem.

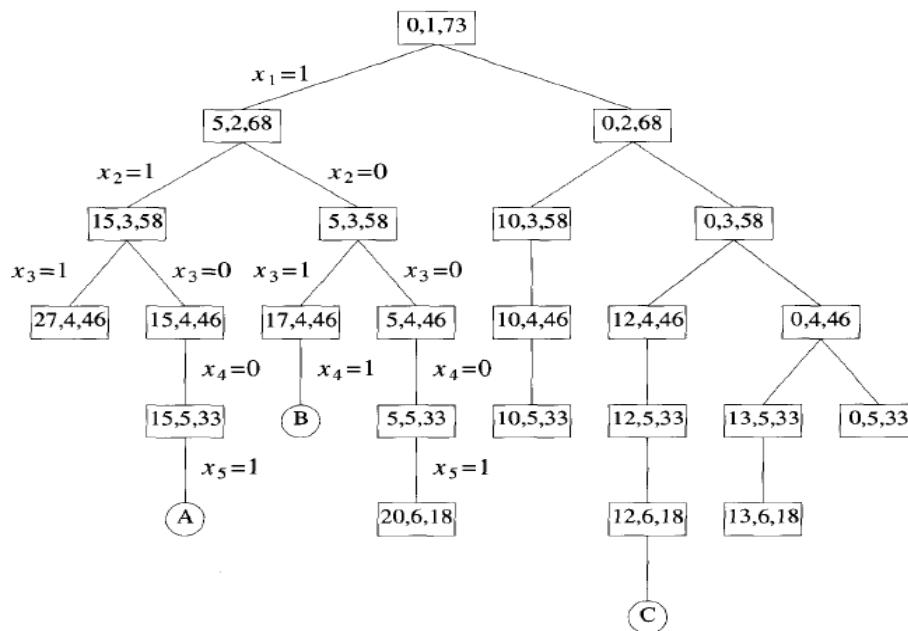
The tree corresponds to the variable tuple size formulation. The edges are labeled such that an edge from a level  $i$  node to a level  $i+1$  node represents a value for  $x_i$ . At each node, the solution space is partitioned into sub-solution spaces. All paths from the root node to any node in the tree define the solution space, since any such path corresponds to a subset satisfying the explicit constraints.

The possible paths are (1), (1, 2), (1, 2, 3), (1, 2, 3, 4), (1, 2, 4), (1, 3, 4), (2), (2, 3), and so on. Thus, the left most sub-tree defines all subsets containing  $w_1$ , the next sub-tree defines all subsets containing  $w_2$  but not  $w_1$ , and so on.

```

1  Algorithm SumOfSub( $s, k, r$ )
2  // Find all subsets of  $w[1 : n]$  that sum to  $m$ . The values of  $x[j]$ ,
3  //  $1 \leq j < k$ , have already been determined.  $s = \sum_{j=1}^{k-1} w[j] * x[j]$ 
4  // and  $r = \sum_{j=k}^n w[j]$ . The  $w[j]$ 's are in nondecreasing order.
5  // It is assumed that  $w[1] \leq m$  and  $\sum_{i=1}^n w[i] \geq m$ .
6  {
7      // Generate left child. Note:  $s + w[k] \leq m$  since  $B_{k-1}$  is true.
8       $x[k] := 1$ ;
9      if ( $s + w[k] = m$ ) then write ( $x[1 : k]$ ); // Subset found
10     // There is no recursive call here as  $w[j] > 0$ ,  $1 \leq j \leq n$ .
11     else if ( $s + w[k] + w[k+1] \leq m$ )
12         then SumOfSub( $s + w[k], k + 1, r - w[k]$ );
13     // Generate right child and evaluate  $B_k$ .
14     if (( $s + r - w[k] \geq m$ ) and ( $s + w[k+1] \leq m$ )) then
15     {
16          $x[k] := 0$ ;
17         SumOfSub( $s, k + 1, r - w[k]$ );
18     }
19 }
```

**Algorithm 7.6** Recursive backtracking algorithm for sum of subsets problem



**Figure 7.10** Portion of state space tree generated by SumOfSub

## **Graph Coloring (for planar graphs):**

Let  $G$  be a graph and  $m$  be a given positive integer. We want to discover whether the nodes of  $G$  can be colored in such a way that no two adjacent nodes have the same color, yet only  $m$  colors are used. This is termed the  $m$ -colorability decision problem. The  $m$ -colorability optimization problem asks for the smallest integer  $m$  for which the graph  $G$  can be colored.

Given any map, if the regions are to be colored in such a way that no two adjacent regions have the same color, only four colors are needed.

For many years it was known that five colors were sufficient to color any map, but no map that required more than four colors had ever been found. After several hundred years, this problem was solved by a group of mathematicians with the help of a computer. They showed that in fact four colors are sufficient for planar graphs.

The function  $m$ -coloring will begin by first assigning the graph to its adjacency matrix, setting the array  $x []$  to zero. The colors are represented by the integers  $1, 2, \dots, m$  and the solutions are given by the  $n$ -tuple  $(x_1, x_2, \dots, x_n)$ , where  $x_i$  is the color of node  $i$ .

A recursive backtracking algorithm for graph coloring is carried out by invoking the statement `mcoloring(1);`

### **Algorithm mcoloring (k)**

```
// This algorithm was formed using the recursive backtracking schema. The graph is
// represented by its Boolean adjacency matrix G [1: n, 1: n]. All assignments of
// 1, 2, ..... , m to the vertices of the graph such that adjacent vertices are assigned
// distinct integers are printed. k is the index of the next vertex to color.
{
    repeat
    {
        NextValue (k);           // Assign to x [k] a legal color.
        If (x [k] = 0) then return; // No new color possible
        If (k = n) then          // at most m colors have been
                                // used to color the n vertices.
            write (x [1: n]);
            else mcoloring (k+1);
    } until (false);
}
```

### **Algorithm NextValue (k)**

```
// x [1], .....x [k-1] have been assigned integer values in the range [1, m] such that
// adjacent vertices have distinct integers. A value for x [k] is determined in the range
// [0, m].x[k] is assigned the next highest numbered color while maintaining distinctness
// from the adjacent vertices of vertex k. If no such color exists, then x [k] is 0.
{
    repeat
    {
        x [k]: = (x [k] +1) mod (m+1)           // Next highest color.
        If (x [k] = 0) then return;               // All colors have been used
        for j := 1 to n do
        {
            // check if this color is distinct from adjacent colors
            if ((G [k, j] ≠ 0) and (x [k] = x [j]))
                // If (k, j) is an edge and if adj. vertices have the same color.
                then break;
```

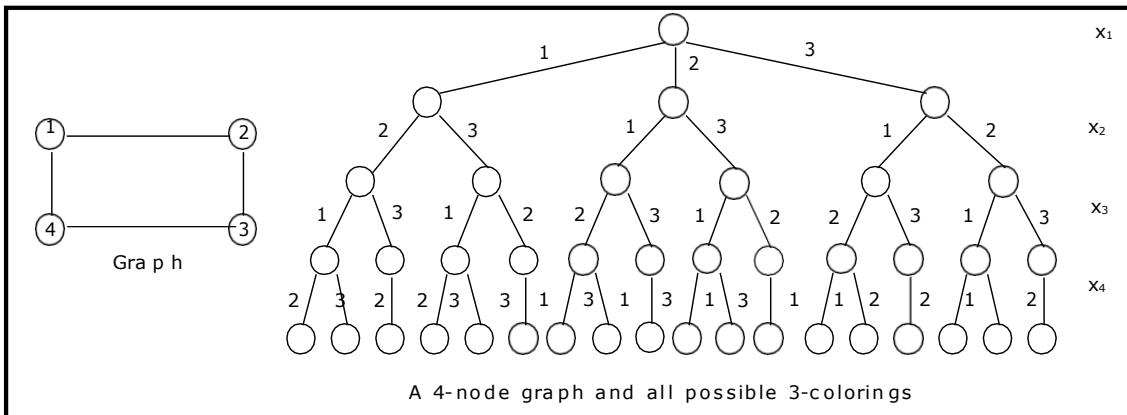
```

        }
        if (j = n+1) then return;           // New color found
    } until (false);                  // Otherwise try to find another color.
}

```

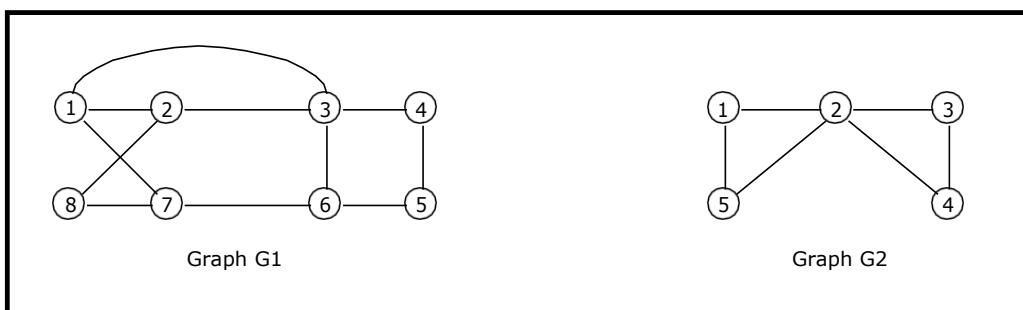
### Example:

Color the graph given below with minimum number of colors by backtracking using state space tree



### Hamiltonian Cycles:

Let  $G = (V, E)$  be a connected graph with  $n$  vertices. A Hamiltonian cycle (suggested by William Hamilton) is a round-trip path along  $n$  edges of  $G$  that visits every vertex once and returns to its starting position. In other vertices of  $G$  are visited in the order  $v_1, v_2, \dots, v_{n+1}$ , then the edges  $(v_i, v_{i+1})$  are in  $E$ ,  $1 \leq i \leq n$ , and the  $v_i$  are distinct except for  $v_1$  and  $v_{n+1}$ , which are equal. The graph  $G_1$  contains the Hamiltonian cycle  $1, 2, 8, 7, 6, 5, 4, 3, 1$ . The graph  $G_2$  contains no Hamiltonian cycle.



Two graphs to illustrate Hamiltonian cycle

The backtracking solution vector  $(x_1, \dots, x_n)$  is defined so that  $x_i$  represents the  $i^{\text{th}}$  visited vertex of the proposed cycle. If  $k = 1$ , then  $x_1$  can be any of the  $n$  vertices. To avoid printing the same cycle  $n$  times, we require that  $x_1 = 1$ . If  $1 < k < n$ , then  $x_k$  can be any vertex  $v$  that is distinct from  $x_1, x_2, \dots, x_{k-1}$  and  $v$  is connected by an edge to  $x_{k-1}$ . The vertex  $x_n$  can only be one remaining vertex and it must be connected to both  $x_{n-1}$  and  $x_1$ .

Using NextValue algorithm we can particularize the recursive backtracking schema to find all Hamiltonian cycles. This algorithm is started by first initializing the adjacency

matrix  $G[1: n, 1: n]$ , then setting  $x[2: n]$  to zero and  $x[1]$  to 1, and then executing Hamiltonian(2).

The traveling salesperson problem using dynamic programming asked for a tour that has minimum cost. This tour is a Hamiltonian cycles. For the simple case of a graph all of whose edge costs are identical, Hamiltonian will find a minimum-cost tour if a tour exists.

**Algorithm NextValue (k)**

```
// x [1: k-1] is a path of k - 1 distinct vertices . If x[k] = 0, then no vertex has as yet been
// assigned to x [k]. After execution, x[k] is assigned to the next highest numberedvertex
// which does not already appear in x [1 : k - 1] and is connected by an edge to x [k - 1].
// Otherwise x [k] = 0. If k = n, then in addition x [k] is connected to x [1].
{
    repeat
    {
        x [k] := (x [k] +1) mod (n+1);           // Next vertex.
        If (x [k] = 0) then return;
        If (G [x [k - 1], x [k]] ≠ 0) then
        {
            // Is there an edge?
            for j := 1 to k - 1 do if (x [j] = x [k]) then break;
            // check for distinctness.
            If (j = k) then           // If true, then the vertex is distinct.
            If ((k < n) or ((k = n) and G [x [n], x [1]] ≠ 0))
            then return;
        }
    } until (false);
}
```

**Algorithm Hamiltonian (k)**

```
// This algorithm uses the recursive formulation of backtracking to find all the Hamiltonian
// cycles of a graph. The graph is stored as an adjacency matrix G [1: n, 1: n]. All cycles begin
// at node 1.
{
    repeat
    {
        NextValue (k);                      // Generate values for x [k].
        //Assign a legal Next value to x [k].
        if (x [k] = 0) then return;
        if (k = n) then write (x [1: n]);
        else Hamiltonian (k + 1)
    } until (false);
}
```

**UNIT V:**

**Branch and Bound:** General method, applications - Travelling sales person problem, 0/1 knapsack problem- LC Branch and Bound solution, FIFO Branch and Bound solution.

**NP-Hard and NP-Complete problems:** Basic concepts, non deterministic algorithms, NP - Hard and NPComplete classes, Cook's theorem.

# Branch and Bound

## General method:

Branch and Bound is another method to systematically search a solution space. Just like backtracking, we will use bounding functions to avoid generating subtrees that do not contain an answer node. However branch and Bound differs from backtracking in two important manners:

1. It has a branching function, which can be a depth first search, breadth first search or based on bounding function.
2. It has a bounding function, which goes far beyond the feasibility test as a mean to prune efficiently the search tree.

Branch and Bound refers to all state space search methods in which all children of the E-node are generated before any other live node becomes the E-node

Branch and Bound is the generalization of both graph search strategies, BFS and D-search.

- A BFS like state space search is called as FIFO (First in first out) search as the list of live nodes in a first in first out list (or queue).
- A D search like state space search is called as LIFO (Last in first out) search as the list of live nodes in a last in first out (or stack).

*Definition 1:* Live node is a node that has been generated but whose children have not yet been generated.

*Definition 2:* E-node is a live node whose children are currently being explored. In other words, an E-node is a node currently being expanded.

*Definition 3:* Dead node is a generated node that is not to be expanded or explored any further. All children of a dead node have already been expanded.

*Definition 4:* Branch-and-bound refers to all state space search methods in which all children of an E-node are generated before any other live node can become the E-node.

*Definition 5:* The adjective "heuristic", means "related to improving problem solving performance". As a noun it is also used in regard to "any method or trick used to improve the efficiency of a problem solving problem". But imperfect methods are not necessarily heuristic or vice versa. "A heuristic (heuristic rule, heuristic method) is a rule of thumb, strategy, trick simplification or any other kind of device which drastically limits search for solutions in large problem spaces. Heuristics do not guarantee optimal solutions, they do not guarantee any solution at all. A useful heuristic offers solutions which are good enough most of the time.

### **Least Cost (LC) search:**

In both LIFO and FIFO Branch and Bound the selection rule for the next E-node is rigid and blind. The selection rule for the next E-node does not give any preference to a node that has a very good chance of getting the search to an answer node quickly.

The search for an answer node can be speeded by using an "intelligent" ranking function  $c(\cdot)$  for live nodes. The next E-node is selected on the basis of this ranking function. The node  $x$  is assigned a rank using:

$$c(x) = f(h(x)) + g(x)$$

where,  $c(x)$  is the cost of  $x$ .

$h(x)$  is the cost of reaching  $x$  from the root and  $f(\cdot)$  is any non-decreasing function.

$g(x)$  is an estimate of the additional effort needed to reach an answer node from  $x$ .

A search strategy that uses a cost function  $c(x) = f(h(x)) + g(x)$  to select the next E-node would always choose for its next E-node a live node with least  $c(\cdot)$  is called a LC-search (Least Cost search)

BFS and D-search are special cases of LC-search. If  $g(x) = 0$  and  $f(h(x)) = \text{level of node } x$ , then an LC search generates nodes by levels. This is eventually the same as a BFS. If  $f(h(x)) = 0$  and  $g(x) > g(y)$  whenever  $y$  is a child of  $x$ , then the search is essentially a D-search.

An LC-search coupled with bounding functions is called an LC-branch and bound search

We associate a cost  $c(x)$  with each node  $x$  in the state space tree. It is not possible to easily compute the function  $c(x)$ . So we compute a estimate  $\hat{c}(x)$  of  $c(x)$ .

### **Control Abstraction for LC-Search:**

Let  $t$  be a state space tree and  $c(\cdot)$  a cost function for the nodes in  $t$ . If  $x$  is a node in  $t$ , then  $c(x)$  is the minimum cost of any answer node in the subtree with root  $x$ . Thus,  $c(t)$  is the cost of a minimum-cost answer node in  $t$ .

A heuristic  $\hat{c}(\cdot)$  is used to estimate  $c(\cdot)$ . This heuristic should be easy to compute and generally has the property that if  $x$  is either an answer node or a leaf node, then  $c(x) = \hat{c}(x)$ .

LC-search uses  $\hat{c}$  to find an answer node. The algorithm uses two functions Least() and Add() to delete and add a live node from or to the list of live nodes, respectively.

Least() finds a live node with least  $c(\cdot)$ . This node is deleted from the list of live nodes and returned.

Add( $x$ ) adds the new live node  $x$  to the list of live nodes. The list of live nodes be implemented as a min-heap.

Algorithm LCSearch outputs the path from the answer node it finds to the root node  $t$ . This is easy to do if with each node  $x$  that becomes live, we associate a field *parent* which gives the parent of node  $x$ . When the answer node  $g$  is found, the path from  $g$  to  $t$  can be determined by following a sequence of *parent* values starting from the current E-node (which is the parent of  $g$ ) and ending at node  $t$ .

```
Listnode = record
{
    Listnode * next, *parent; float cost;
}

Algorithm LCSearch(t)
{
    //Search t for an answer node
    if *t is an answer node then output *t and return;
    E := t;           //E-node.
    initialize the list of live nodes to be empty;
    repeat
    {
        for each child x of E do
        {
            if x is an answer node then output the path from x to t and return;
            Add (x);           //x is a new live node.
            (x → parent) := E; // pointer for path to root
        }
        if there are no more live nodes then
        {
            write ("No answer node");
            return;
        }
        E := Least();
    } until (false);
}
```

The root node is the first, E-node. During the execution of LC search, this list contains all live nodes except the E-node. Initially this list should be empty. Examine all the children of the E-node, if one of the children is an answer node, then the algorithm outputs the path from  $x$  to  $t$  and terminates. If the child of  $E$  is not an answer node, then it becomes a live node. It is added to the list of live nodes and its parent field set to  $E$ . When all the children of  $E$  have been generated,  $E$  becomes a dead node. This happens only if none of  $E$ 's children is an answer node. Continue the search further until no live nodes found. Otherwise, Least(), by definition, correctly chooses the next E-node and the search continues from here.

LC search terminates only when either an answer node is found or the entire state space tree has been generated and searched.

### **Bounding:**

A branch and bound method searches a state space tree using any search mechanism in which all the children of the E-node are generated before another node becomes the E-node. We assume that each answer node  $x$  has a cost  $c(x)$  associated with it and that a minimum-cost answer node is to be found. Three common search strategies are FIFO, LIFO, and LC. The three search methods differ only in the selection rule used to obtain the next E-node.

A good bounding helps to prune efficiently the tree, leading to a faster exploration of the solution space.

A cost function  $c(\cdot)$  such that  $c(x) \leq c(x)$  is used to provide lower bounds on solutions obtainable from any node  $x$ . If  $\text{upper}$  is an upper bound on the cost of a minimum-cost solution, then all live nodes  $x$  with  $c(x) \geq c(x) > \text{upper}$ . The starting value for  $\text{upper}$  can be obtained by some heuristic or can be set to  $\infty$ .

As long as the initial value for  $\text{upper}$  is not less than the cost of a minimum-cost answer node, the above rules to kill live nodes will not result in the killing of a live node that can reach a minimum-cost answer node. Each time a new answer node is found, the value of  $\text{upper}$  can be updated.

Branch-and-bound algorithms are used for optimization problems where, we deal directly only with minimization problems. A maximization problem is easily converted to a minimization problem by changing the sign of the objective function.

To formulate the search for an optimal solution for a least-cost answer node in a state space tree, it is necessary to define the cost function  $c(\cdot)$ , such that  $c(x)$  is minimum for all nodes representing an optimal solution. The easiest way to do this is to use the objective function itself for  $c(\cdot)$ .

- For nodes representing feasible solutions,  $c(x)$  is the value of the objective function for that feasible solution.
- For nodes representing infeasible solutions,  $c(x) = \infty$ .
- For nodes representing partial solutions,  $c(x)$  is the cost of the minimum-cost node in the subtree with root  $x$ .

Since,  $c(x)$  is generally hard to compute, the branch-and-bound algorithm will use an estimate  $\hat{c}(x)$  such that  $\hat{c}(x) \leq c(x)$  for all  $x$ .

### **FIFO Branch and Bound:**

A FIFO branch-and-bound algorithm for the job sequencing problem can begin with  $\text{upper} = \infty$  as an upper bound on the cost of a minimum-cost answer node.

Starting with node 1 as the E-node and using the variable tuple size formulation of Figure 8.4, nodes 2, 3, 4, and 5 are generated. Then  $u(2) = 19$ ,  $u(3) = 14$ ,  $u(4) = 18$ , and  $u(5) = 21$ .

The variable  $\text{upper}$  is updated to 14 when node 3 is generated. Since  $\hat{c}(4)$  and  $\hat{c}(5)$  are greater than  $\text{upper}$ , nodes 4 and 5 get killed. Only nodes 2 and 3 remain alive.

Node 2 becomes the next E-node. Its children, nodes 6, 7 and 8 are generated. Then  $u(6) = 9$  and so  $\text{upper}$  is updated to 9. The cost  $\hat{c}(7) = 10 > \text{upper}$  and node 7 gets killed. Node 8 is infeasible and so it is killed.

Next, node 3 becomes the E-node. Nodes 9 and 10 are now generated. Then  $u(9) = 8$  and so  $\text{upper}$  becomes 8. The cost  $\hat{c}(10) = 11 > \text{upper}$ , and this node is killed.

The next E-node is node 6. Both its children are infeasible. Node 9's only child is also infeasible. The minimum-cost answer node is node 9. It has a cost of 8.

When implementing a FIFO branch-and-bound algorithm, it is not economical to kill live nodes with  $c(x) > \text{upper}$  each time upper is updated. This is so because live nodes are in the queue in the order in which they were generated. Hence, nodes with  $c(x) > \text{upper}$  are distributed in some random way in the queue. Instead, live nodes with  $c(x) > \text{upper}$  can be killed when they are about to become E-nodes.

The FIFO-based branch-and-bound algorithm with an appropriate  $c(\cdot)$  and  $u(\cdot)$  is called FIFOBB.

### **LC Branch and Bound:**

An LC Branch-and-Bound search of the tree of Figure 8.4 will begin with  $\text{upper} = \infty$  and node 1 as the first E-node.

When node 1 is expanded, nodes 2, 3, 4 and 5 are generated in that order.

As in the case of FIFOBB, upper is updated to 14 when node 3 is generated and nodes 4 and 5 are killed as  $c(4) > \text{upper}$  and  $c(5) > \text{upper}$ .

Node 2 is the next E-node as  $c(2) = 0$  and  $c(3) = 5$ . Nodes 6, 7 and 8 are generated and upper is updated to 9 when node 6 is generated. So, node 7 is killed as  $c(7) = 10 > \text{upper}$ . Node 8 is infeasible and so killed. The only live nodes now are nodes 3 and 6.

Node 6 is the next E-node as  $c(6) = 0 < c(3)$ . Both its children are infeasible.

Node 3 becomes the next E-node. When node 9 is generated, upper is updated to 8 as  $u(9) = 8$ . So, node 10 with  $c(10) = 11$  is killed on generation.

Node 9 becomes the next E-node. Its only child is infeasible. No live nodes remain. The search terminates with node 9 representing the minimum-cost answer node.

$$\begin{array}{cc} 2 & 3 \\ \text{The path} = 1 \rightarrow 3 \rightarrow 9 = 5 + 3 = 8 \end{array}$$

### **Traveling Sale Person Problem:**

By using dynamic programming algorithm we can solve the problem with time complexity of  $O(n^2 2^n)$  for worst case. This can be solved by branch and bound technique using efficient bounding function. The time complexity of traveling sale person problem using LC branch and bound is  $O(n^2 2^n)$  which shows that there is no change or reduction of complexity than previous method.

We start at a particular node and visit all nodes exactly once and come back to initial node with minimum cost.

Let  $G = (V, E)$  is a connected graph. Let  $C(i, j)$  be the cost of edge  $\langle i, j \rangle$ .  $c_{ij} = \infty$  if  $\langle i, j \rangle \notin E$  and let  $|V| = n$ , the number of vertices. Every tour starts at vertex 1 and ends at the same vertex. So, the solution space is given by  $S = \{1, \pi, 1 \mid \pi \text{ is a}$

permutation of  $(2, 3, \dots, n)\}$  and  $|S| = (n - 1)!$ . The size of S can be reduced by restricting S so that  $(1, i_1, i_2, \dots, i_{n-1}, 1) \in S$  iff  $\langle i_j, i_{j+1} \rangle \in E$ ,  $0 \leq j \leq n - 1$  and  $i_0 = i_n = 1$ .

Procedure for solving traveling sale person problem:

1. Reduce the given cost matrix. A matrix is reduced if every row and column is reduced. A row (column) is said to be reduced if it contain at least one zero and all-remaining entries are non-negative. This can be done as follows:

- a) *Row reduction:* Take the minimum element from first row, subtract it from all elements of first row, next take minimum element from the second row and subtract it from second row. Similarly apply the same procedure for all rows.
- b) Find the sum of elements, which were subtracted from rows.
- c) Apply column reductions for the matrix obtained after row reduction.

*Column reduction:* Take the minimum element from first column, subtract it from all elements of first column, next take minimum element from the second column and subtract it from second column. Similarly apply the same procedure for all columns.

- d) Find the sum of elements, which were subtracted from columns.
- e) Obtain the cumulative sum of row wise reduction and column wise reduction.

Cumulative reduced sum = Row wise reduction sum + column wise reduction sum.

Associate the cumulative reduced sum to the starting state as lower bound and  $\infty$  as upper bound.

2. Calculate the reduced cost matrix for every node R. Let A is the reduced cost matrix for node R. Let S be a child of R such that the tree edge  $(R, S)$  corresponds to including edge  $\langle i, j \rangle$  in the tour. If S is not a leaf node, then the reduced cost matrix for S may be obtained as follows:

- a) Change all entries in row i and column j of A to  $\infty$ .
- b) Set  $A(j, 1)$  to  $\infty$ .
- c) Reduce all rows and columns in the resulting matrix except for rows and column containing only  $\infty$ . Let r is the total amount subtracted to reduce the matrix.
- c) Find  $c(S) = c(R) + A(i, j) + r$ , where 'r' is the total amount subtracted to reduce the matrix,  $c(R)$  indicates the lower bound of the  $i^{\text{th}}$  node in  $(i, j)$  path and  $c(S)$  is called the cost function.

3. Repeat step 2 until all nodes are visited.

**Example:**

Find the LC branch and bound solution for the traveling sale person problem whose cost matrix is as follows:

$$\text{The cost matrix is } \begin{bmatrix} \infty & 20 & 30 & 10 & 11 \\ 15 & \infty & 16 & 4 & 2 \\ 35 & \infty & 2 & 4 \\ 19 & 6 & 18 & \infty & 3 \\ 16 & 4 & 7 & 16 & \infty \end{bmatrix}$$

*Step 1: Find the reduced cost matrix.*

*Apply row reduction method:*

*Deduct 10 (which is the minimum) from all values in the 1<sup>st</sup> row.*

*Deduct 2 (which is the minimum) from all values in the 2<sup>nd</sup> row.*

*Deduct 2 (which is the minimum) from all values in the 3<sup>rd</sup> row.*

*Deduct 3 (which is the minimum) from all values in the 4<sup>th</sup> row.*

*Deduct 4 (which is the minimum) from all values in the 5<sup>th</sup> row.*

$$\text{The resulting row wise reduced cost matrix} = \begin{bmatrix} \infty & 10 & 20 & 0 & 1 \\ 13 & \infty & 14 & 2 & 0 \\ 1 & 3 & \infty & 0 & 0 \\ 16 & 3 & 15 & \infty & 0 \\ 12 & 0 & 3 & 12 & \infty \end{bmatrix}$$

$$\text{Row wise reduction sum} = 10 + 2 + 2 + 3 + 4 = 21$$

Now apply column reduction for the above matrix:

*Deduct 1 (which is the minimum) from all values in the 1<sup>st</sup> column.*

*Deduct 3 (which is the minimum) from all values in the 3<sup>rd</sup> column.*

$$\text{The resulting column wise reduced cost matrix (A)} = \begin{bmatrix} \infty & 10 & 17 & 0 & 1 \\ 12 & \infty & 11 & 2 & 0 \\ 0 & 3 & \infty & 0 & 2 \\ 15 & 3 & 12 & \infty & 0 \\ 11 & 0 & 0 & 12 & \infty \end{bmatrix}$$

$$\text{Column wise reduction sum} = 1 + 0 + 3 + 0 + 0 = 4$$

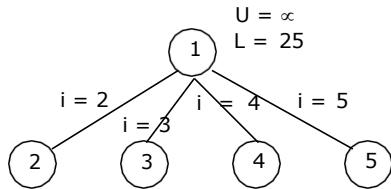
$$\begin{aligned} \text{Cumulative reduced sum} &= \text{row wise reduction} + \text{column wise reduction sum.} \\ &= 21 + 4 = 25. \end{aligned}$$

This is the cost of a root i.e., node 1, because this is the initially reduced costmatrix.

The lower bound for node is 25 and upper bound is  $\infty$ .

Starting from node 1, we can next visit 2, 3, 4 and 5 vertices. So, consider to explore the paths (1, 2), (1, 3), (1, 4) and (1, 5).

The tree organization up to this point is as follows:



Variable 'i' indicates the next node to visit.

*Step 2:*

*Consider the path (1, 2):*

Change all entries of row 1 and column 2 of A to  $\infty$  and also set  $A(2, 1)$  to  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & 11 & 2 & 0 \\ 0 & \infty & \infty & 0 & 2 \\ 15 & \infty & 12 & \infty & 0 \\ 11 & \infty & 0 & 12 & \infty \end{bmatrix}$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

Then the resultant matrix is

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & 11 & 2 & 0 \\ 0 & \infty & \infty & 0 & 2 \\ 15 & \infty & 12 & \infty & 0 \\ 11 & \infty & 0 & 12 & \infty \end{bmatrix}$$

$$\text{Row reduction sum} = 0 + 0 + 0 + 0 = 0$$

$$\text{Column reduction sum} = 0 + 0 + 0 + 0 = 0$$

$$\text{Cumulative reduction (r)} = 0 + 0 = 0$$

Therefore, as  $c(S) = c(R) + A(1, 2) + r$   
 $c(S) = 25 + 10 + 0 = 35$

*Consider the path (1, 3):*

Change all entries of row 1 and column 3 of A to  $\infty$  and also set  $A(3, 1)$  to  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 12 & \infty & \infty & 2 & 0 \\ \infty & 3 & \infty & 0 & 2 \\ 15 & 3 & \infty & \infty & 0 \\ 11 & 0 & \infty & 12 & \infty \end{bmatrix}$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 1 & \infty & \infty & 2 & 0 \\ \infty & 3 & \infty & 0 & 2 \\ 4 & 3 & \infty & \infty & 0 \\ 0 & 0 & \infty & 12 & \infty \end{bmatrix}$$

Row reduction sum = 0

Column reduction sum = 11

Cumulative reduction (r) = 0 + 11 = 11

$$\text{Therefore, as } \hat{c}(S) = \hat{c}(R) + A(1, 3) + r \\ \hat{c}(S) = 25 + 17 + 11 = 53$$

*Consider the path (1, 4):*

Change all entries of row 1 and column 4 of A to  $\infty$  and also set A(4, 1) to  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 12 & \infty & 11 & \infty & 0 \\ 0 & 3 & \infty & \infty & 2 \\ \infty & 3 & 12 & \infty & 0 \\ 11 & 0 & 0 & \infty & \infty \end{bmatrix}$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 12 & \infty & 11 & \infty & 0 \\ 0 & 3 & \infty & \infty & 2 \\ \infty & 3 & 12 & \infty & 0 \\ 11 & 0 & 0 & \infty & \infty \end{bmatrix}$$

Row reduction sum = 0

Column reduction sum = 0

Cumulative reduction (r) = 0 + 0 = 0

$$\text{Therefore, as } c(S) = c(R) + A(1, 4) + r$$

$$c(S) = 25 + 0 + 0 = 25$$

Consider the path (1, 5):

Change all entries of row 1 and column 5 of A to  $\infty$  and also set  $A(5, 1)$  to  $\infty$ .

$$\left[ \begin{array}{ccccc} \infty & \infty & \infty & \infty & \infty \\ 12 & \infty & 11 & 2 & \infty \\ 0 & 3 & \infty & 0 & \infty \\ 15 & 3 & 12 & \infty & \infty \\ \infty & 0 & 0 & 12 & \infty \end{array} \right]$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

Then the resultant matrix is

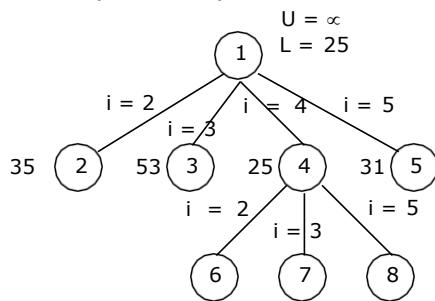
$$\left[ \begin{array}{ccccc} \infty & \infty & \infty & \infty & \infty \\ 10 & \infty & 9 & 0 & \infty \\ 0 & 3 & \infty & 0 & \infty \\ 12 & 0 & 9 & \infty & \infty \\ \infty & 0 & 0 & 12 & \infty \end{array} \right]$$

Row reduction sum = 5  
 Column reduction sum = 0  
 Cumulative reduction ( $r$ ) =  $5 + 0 = 0$

$$\text{Therefore, as } c(S) = c(R) + A(1, 5) + r$$

$$c(S) = 25 + 1 + 0 = 31$$

The tree organization up to this point is as follows:



The cost of the paths between (1, 2) = 35, (1, 3) = 53, (1, 4) = 25 and (1, 5) = 31. The cost of the path between (1, 4) is minimum. Hence the matrix obtained for path (1, 4) is considered as reduced cost matrix.

$$A = \begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 12 & \infty & 11 & \infty & 0 \\ 0 & 3 & \infty & \infty & 2 \\ \infty & 3 & 12 & \infty & 0 \\ 11 & 0 & 0 & \infty & \infty \end{bmatrix}$$

The new possible paths are (4, 2), (4, 3) and (4, 5).

Consider the path (4, 2):

Change all entries of row 4 and column 2 of A to  $\infty$  and also set  $A(2, 1)$  to  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & 11 & \infty & 0 \\ 0 & \infty & \infty & \infty & 2 \\ \infty & \infty & \infty & \infty & \infty \\ 11 & \infty & 0 & \infty & \infty \end{bmatrix}$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & 11 & \infty & 0 \\ 0 & \infty & \infty & \infty & 2 \\ \infty & \infty & \infty & \infty & \infty \\ 11 & \infty & 0 & \infty & \infty \end{bmatrix}$$

Row reduction sum = 0

Column reduction sum = 0

Cumulative reduction ( $r$ ) =  $0 + 0 = 0$

$$\text{Therefore, as } c(S) = c(R) + A(4, 2) + r \\ c(S) = 25 + 3 + 0 = 28$$

Consider the path (4, 3):

Change all entries of row 4 and column 3 of A to  $\infty$  and also set  $A(3, 1)$  to  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 12 & \infty & \infty & \infty & 0 \\ \infty & 3 & \infty & \infty & 2 \\ \infty & \infty & \infty & \infty & \infty \\ 11 & 0 & \infty & \infty & \infty \end{bmatrix}$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 1 & \infty & \infty & \infty & 0 \\ \hline | & \infty & 1 & \infty & \infty & 0 \\ | & \infty & \infty & \infty & \infty & \infty \\ \hline | & 0 & 0 & \infty & \infty & \infty \end{bmatrix}$$

Then the resultant matrix is

Row reduction sum = 2

Column reduction sum = 11

Cumulative reduction (r) = 2 + 11 = 13

$$\text{Therefore, as } c(S) = c(R) + A(4, 3) + r \\ c(S) = 25 + 12 + 13 = 50$$

Consider the path (4, 5):

Change all entries of row 4 and column 5 of A to  $\infty$  and also set A(5, 1) to  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 12 & \infty & 11 & \infty & \infty \\ \hline | & 0 & 3 & \infty & \infty & \infty \\ | & \infty & \infty & \infty & \infty & \infty \\ \hline | & \infty & 0 & 0 & \infty & \infty \end{bmatrix}$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ 1 & \infty & 0 & \infty & \infty \\ \hline | & 0 & 3 & \infty & \infty & \infty \\ | & \infty & \infty & \infty & \infty & \infty \\ \hline | & \infty & 0 & 0 & \infty & \infty \end{bmatrix}$$

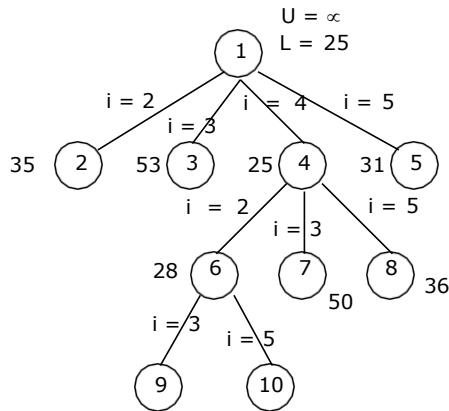
Row reduction sum = 11

Column reduction sum = 0

Cumulative reduction (r) = 11+0 = 11

$$\text{Therefore, as } c(S) = c(R) + A(4, 5) + r \\ c(S) = 25 + 0 + 11 = 36$$

The tree organization up to this point is as follows:



The cost of the paths between  $(4, 2) = 28$ ,  $(4, 3) = 50$  and  $(4, 5) = 36$ . The cost of the path between  $(4, 2)$  is minimum. Hence the matrix obtained for path  $(4, 2)$  is considered as reduced cost matrix.

$$A = \begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & 11 & \infty & 0 \\ 0 & \infty & \infty & \infty & 2 \\ \infty & \infty & \infty & \infty & \infty \\ 11 & \infty & 0 & \infty & \infty \end{bmatrix}$$

*The new possible paths are  $(2, 3)$  and  $(2, 5)$ .*

*Consider the path  $(2, 3)$ :*

Change all entries of row 2 and column 3 of A to  $\infty$  and also set  $A(3, 1)$  to  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & 2 \\ \infty & \infty & \infty & \infty & \infty \\ 11 & \infty & 0 & \infty & \infty \end{bmatrix}$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

Then the resultant matrix is

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & 0 \\ \infty & \infty & \infty & \infty & \infty \\ 0 & \infty & \infty & \infty & \infty \end{bmatrix}$$

Row reduction sum = 2

Column reduction sum = 11

Cumulative reduction (r) = 2 + 11 = 13

Therefore, as  $c(S) = c(R) + A(2, 3) + r$

$$c(S) = 28 + 11 + 13 = 52$$

Consider the path (2, 5):

Change all entries of row 2 and column 5 of A to  $\infty$  and also set  $A(5, 1)$  to  $\infty$ .

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ 0 & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & 0 & \infty & \infty \end{bmatrix}$$

Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

Then the resultant matrix is

$$\begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ 0 & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & 0 & \infty & \infty \end{bmatrix}$$

Row reduction sum = 0

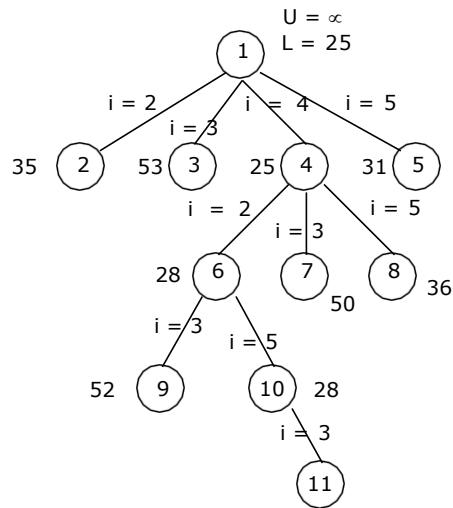
Column reduction sum = 0

Cumulative reduction (r) = 0 + 0 = 0

Therefore, as  $c(S) = c(R) + A(2, 5) + r$

$$c(S) = 28 + 0 + 0 = 28$$

The tree organization up to this point is as follows:



The cost of the paths between (2, 3) = 52 and (2, 5) = 28. The cost of the path between (2, 5) is minimum. Hence the matrix obtained for path (2, 5) is considered as reduced cost matrix.

$$A = \begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ 0 & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & 0 & \infty & \infty \end{bmatrix}$$

The new possible paths is (5, 3).

Consider the path (5, 3):

Change all entries of row 5 and column 3 of A to  $\infty$  and also set  $A(3, 1)$  to  $\infty$ . Apply row and column reduction for the rows and columns whose rows and columns are not completely  $\infty$ .

$$\text{Then the resultant matrix is } \begin{bmatrix} \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty & \infty \end{bmatrix}$$

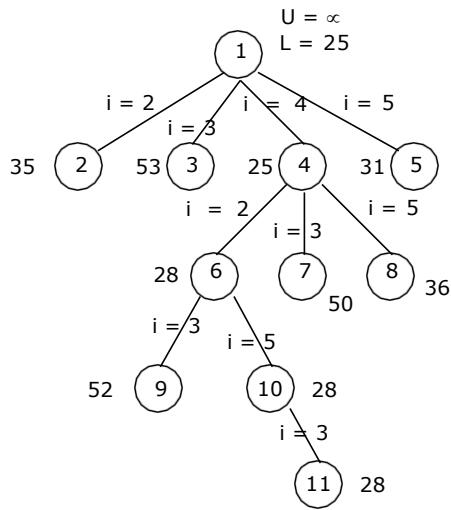
Row reduction sum = 0

Column reduction sum = 0

Cumulative reduction ( $r$ ) =  $0 + 0 = 0$

$$\text{Therefore, as } c(S) = c(R) + A(5, 3) + r \\ c(S) = 28 + 0 + 0 = 28$$

The overall tree organization is as follows:



The path of traveling sale person problem is:

1 → 4 → 2 → 5 → 3 → 1

The minimum cost of the path is:  $10 + 6 + 2 + 7 + 3 = 28$ .

## 0/1 Knapsack Problem

Consider the instance:  $M = 15$ ,  $n = 4$ ,  $(P_1, P_2, P_3, P_4) = (10, 10, 12, 18)$  and  $(w_1, w_2, w_3, w_4) = (2, 4, 6, 9)$ .

0/1 knapsack problem can be solved by using branch and bound technique. In this problem we will calculate lower bound and upper bound for each node.

Place first item in knapsack. Remaining weight of knapsack is  $15 - 2 = 13$ . Place next item  $w_2$  in knapsack and the remaining weight of knapsack is  $13 - 4 = 9$ . Place next item  $w_3$  in knapsack then the remaining weight of knapsack is  $9 - 6 = 3$ . No fractions are allowed in calculation of upper bound so  $w_4$  cannot be placed in knapsack.

$$\text{Profit} = P_1 + P_2 + P_3 = 10 + 10 + 12$$

$$\text{So, Upper bound} = 32$$

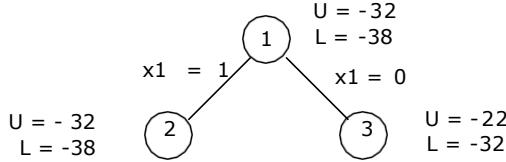
To calculate lower bound we can place  $w_4$  in knapsack since fractions are allowed in calculation of lower bound.

$$\text{Lower bound} = 10 + 10 + 12 + \left(\frac{3}{9} \times 18\right) = 32 + 6 = 38$$

Knapsack problem is maximization problem but branch and bound technique is applicable for only minimization problems. In order to convert maximization problem into minimization problem we have to take negative sign for upper bound and lower bound.

$$\begin{aligned} \text{Therefore, Upper bound (U)} &= -32 \\ \text{Lower bound (L)} &= -38 \end{aligned}$$

We choose the path, which has minimum difference of upper bound and lowerbound. If the difference is equal then we choose the path by comparing upper bounds and we discard node with maximum upper bound.



Now we will calculate upper bound and lower bound for nodes 2, 3.

For node 2,  $x_1 = 1$ , means we should place first item in the knapsack.

$$U = 10 + 10 + 12 = 32, \text{ make it as } -32$$

$$L = 10 + 10 + 12 + \frac{3}{9} \times 18 = 32 + 6 = 38, \text{ make it as } -38$$

For node 3,  $x_1 = 0$ , means we should not place first item in the knapsack.

$$U = 10 + 12 = 22, \text{ make it as } -22$$

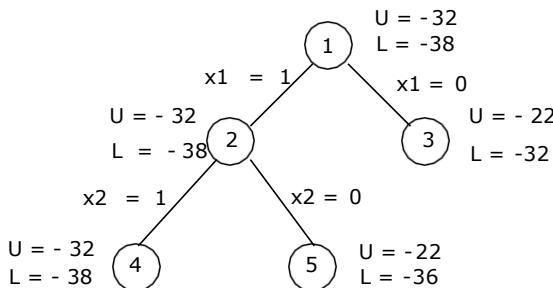
$$L = 10 + 12 + \frac{5}{9} \times 18 = 10 + 12 + 10 = 32, \text{ make it as } -32$$

Next, we will calculate difference of upper bound and lower bound for nodes 2, 3

$$\text{For node 2, } U - L = -32 + 38 = 6$$

$$\text{For node 3, } U - L = -22 + 32 = 10$$

Choose node 2, since it has minimum difference value of 6.

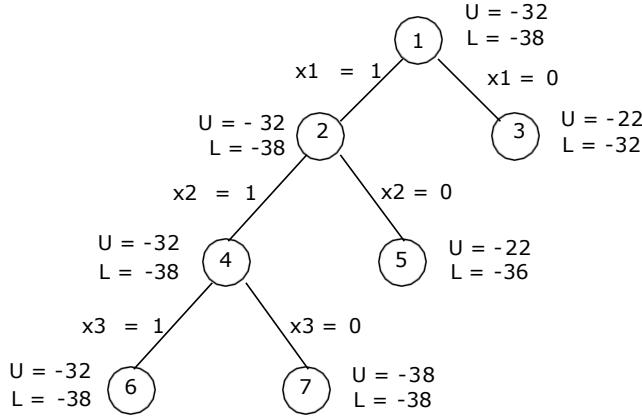


Now we will calculate lower bound and upper bound of node 4 and 5. Calculate difference of lower and upper bound of nodes 4 and 5.

$$\text{For node 4, } U - L = -32 + 38 = 6$$

$$\text{For node 5, } U - L = -22 + 36 = 14$$

Choose node 4, since it has minimum difference value of 6.

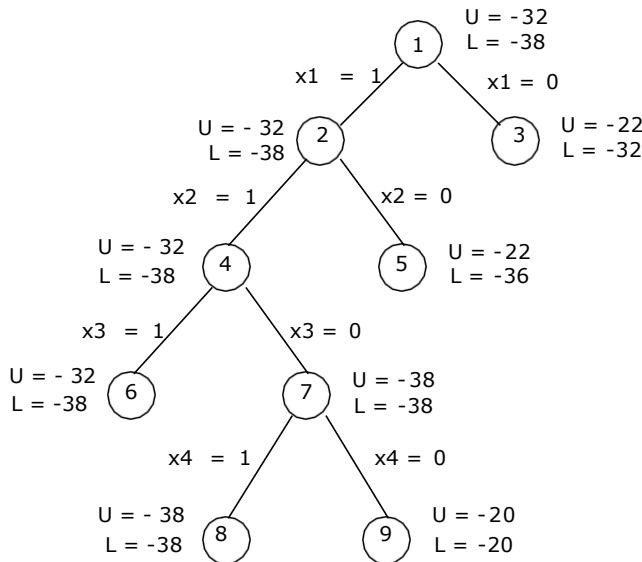


Now we will calculate lower bound and upper bound of node 8 and 9. Calculate difference of lower and upper bound of nodes 8 and 9.

For node 6,  $U - L = -32 + 38 = 6$

For node 7,  $U - L = -38 + 38 = 0$

Choose node 7, since it is minimum difference value of 0.



Now we will calculate lower bound and upper bound of node 4 and 5. Calculate difference of lower and upper bound of nodes 4 and 5.

For node 8,  $U - L = -38 + 38 = 0$

For node 9,  $U - L = -20 + 20 = 0$

Here the difference is same, so compare upper bounds of nodes 8 and 9. Discard the node, which has maximum upper bound. Choose node 8, discard node 9 since, it has maximum upper bound.

Consider the path from  $1 \rightarrow 2 \rightarrow 4 \rightarrow 7 \rightarrow 8$

$$X_1 = 1$$

$$X_2 = 1$$

$$X_3 = 0$$

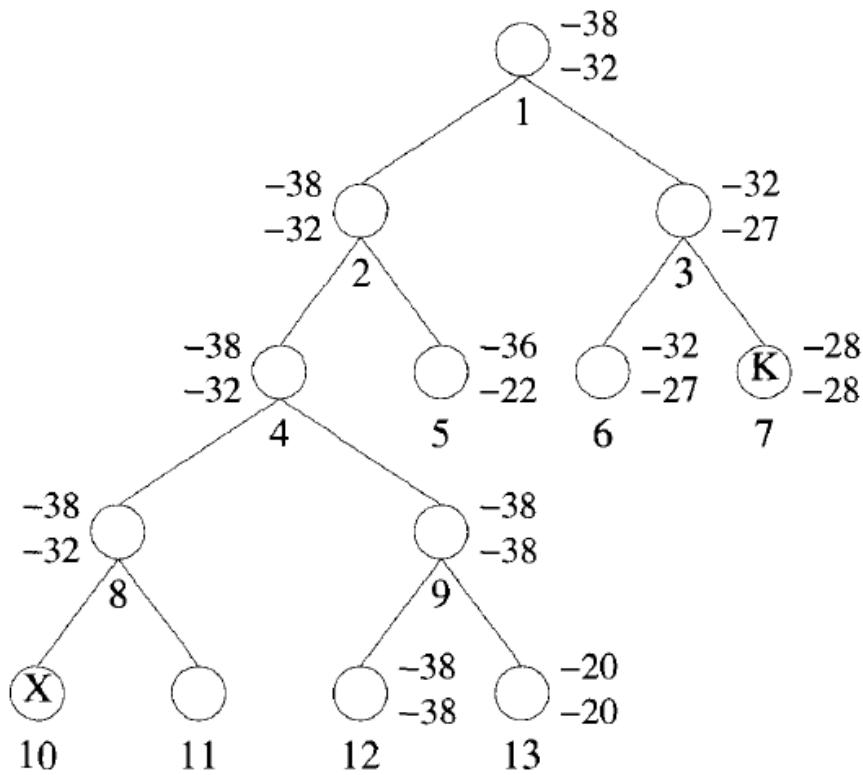
$$X_4 = 1$$

The solution for 0/1 Knapsack problem is  $(x_1, x_2, x_3, x_4) = (1, 1, 0, 1)$

Maximum profit is:

$$\begin{aligned}\sum P_i x_i &= 10 \times 1 + 10 \times 1 + 12 \times 0 + 18 \times 1 \\ &= 10 + 10 + 18 = 38.\end{aligned}$$

**Portion of state space tree using FIFO Branch and Bound for above problem:  
As follows:**



upper number =  $\hat{c}$   
lower number =  $u$

# NP-Hard and NP-Complete problems

## Deterministic and non-deterministic algorithms

**Deterministic:** The algorithm in which every operation is uniquely defined is called deterministic algorithm.

**Non-Deterministic:** The algorithm in which the operations are not uniquely defined but are limited to specific set of possibilities for every operation, such an algorithm is called non-deterministic algorithm.

The non-deterministic algorithms use the following functions:

1. Choice: Arbitrarily chooses one of the element from given set.
2. Failure: Indicates an unsuccessful completion
3. Success: Indicates a successful completion

A **non-deterministic algorithm** terminates unsuccessfully if and only if there exists no set of choices leading to a success signal. Whenever, there is a set of choices that leads to a successful completion, then one such set of choices is selected and the algorithm terminates successfully.

In case the successful completion is not possible, then the complexity is O(1). In case of successful signal completion then the time required is the minimum number of steps needed to reach a successful completion of O(n) where n is the number of inputs.

The problems that are solved in polynomial time are called tractable problems and the problems that require super polynomial time are called non-tractable problems. All deterministic polynomial time algorithms are tractable and the non-deterministic polynomials are intractable.

---

```
1  Algorithm NSort( $A, n$ )
2  // Sort  $n$  positive integers.
3  {
4      for  $i := 1$  to  $n$  do  $B[i] := 0$ ; // Initialize  $B[ ]$ .
5      for  $i := 1$  to  $n$  do
6      {
7           $j := \text{Choice}(1, n)$ ;
8          if  $B[j] \neq 0$  then Failure();
9           $B[j] := A[i]$ ;
10     }
11     for  $i := 1$  to  $n - 1$  do // Verify order.
12         if  $B[i] > B[i + 1]$  then Failure();
13     write ( $B[1 : n]$ );
14     Success();
15 }
```

---

Nondeterministic sorting

---

```

1  Algorithm DKP( $p, w, n, m, r, x$ )
2  {
3       $W := 0; P := 0;$ 
4      for  $i := 1$  to  $n$  do
5      {
6           $x[i] := \text{Choice}(0, 1);$ 
7           $W := W + x[i] * w[i]; P := P + x[i] * p[i];$ 
8      }
9      if  $((W > m) \text{ or } (P < r))$  then Failure();
10     else Success();
11 }

```

---

Nondeterministic knapsack algorithm

### Satisfiability Problem:

The satisfiability is a boolean formula that can be constructed using the following literals and operations.

1. A literal is either a variable or its negation of the variable.
2. The literals are connected with operators  $\vee, \wedge, \Rightarrow, \Leftrightarrow$
3. Parenthesis

The satisfiability problem is to determine whether a Boolean formula is true for some assignment of truth values to the variables. In general, formulas are expressed in Conjunctive Normal Form (CNF).

A Boolean formula is in conjunctive normal form iff it is represented by  
 $(x_i \vee x_j \vee x_k^{-1}) \wedge (x_i \vee x_j^{-1} \vee x_k)$

A Boolean formula is in 3CNF if each clause has exactly 3 distinct literals.

Example:

The non-deterministic algorithm that terminates successfully iff a given formula  $E(x_1, x_2, x_3)$  is satisfiable.

---

```

1  Algorithm Eval( $E$ ,  $n$ )
2  // Determine whether the propositional formula  $E$  is
3  // satisfiable. The variables are  $x_1, x_2, \dots, x_n$ .
4  {
5      for  $i := 1$  to  $n$  do // Choose a truth value assignment.
6           $x_i := \text{Choice}(\text{false}, \text{true})$ ;
7          if  $E(x_1, \dots, x_n)$  then Success();
8          else Failure();
9  }

```

---

### Nondeterministic satisfiability

#### **Reducability:**

A problem  $Q_1$  can be reduced to  $Q_2$  if any instance of  $Q_1$  can be easily rephrased as an instance of  $Q_2$ . If the solution to the problem  $Q_2$  provides a solution to the problem  $Q_1$ , then these are said to be reducable problems.

Let  $L_1$  and  $L_2$  are the two problems.  $L_1$  is reduced to  $L_2$  iff there is a way to solve  $L_1$  by a deterministic polynomial time algorithm using a deterministic algorithm that solves  $L_2$  in polynomial time and is denoted by  $L_1 \alpha L_2$ .

If we have a polynomial time algorithm for  $L_2$  then we can solve  $L_1$  in polynomial time. Two problems  $L_1$  and  $L_2$  are said to be polynomially equivalent iff  $L_1 \alpha L_2$  and  $L_2 \alpha L_1$ .

Example: Let  $P_1$  be the problem of selection and  $P_2$  be the problem of sorting. Let the input have  $n$  numbers. If the numbers are sorted in array  $A[ ]$  the  $i^{\text{th}}$  smallest element of the input can be obtained as  $A[i]$ . Thus  $P_1$  reduces to  $P_2$  in  $O(1)$  time.

#### **Decision Problem:**

Any problem for which the answer is either yes or no is called decision problem. The algorithm for decision problem is called decision algorithm.

Example: Max clique problem, sum of subsets problem.

**Optimization Problem:** Any problem that involves the identification of an optimal value (maximum or minimum) is called optimization problem.

Example: Knapsack problem, travelling salesperson problem.

In decision problem, the output statement is implicit and no explicit statements are permitted.

The output from a decision problem is uniquely defined by the input parameters and algorithm specification.

Many optimization problems can be reduced by decision problems with the property that a decision problem can be solved in polynomial time iff the corresponding optimization problem can be solved in polynomial time. If the decision problem cannot be solved in polynomial time then the optimization problem cannot be solved in polynomial time.

### **Class $P$ :**

$P$ : the class of decision problems that are solvable in  $O(p(n))$  time, where  $p(n)$  is a polynomial of problem's input size  $n$

Examples:

- searching
- element uniqueness
- graph connectivity
- graph acyclicity
- primality testing

### **Class $NP$**

$NP$  (*nondeterministic polynomial*): class of decision problems whose proposed solutions can be verified in polynomial time = solvable by a *nondeterministic polynomial algorithm*

A *nondeterministic polynomial algorithm* is an abstract two-stage procedure that:

- generates a random string purported to solve the problem
- checks whether this solution is correct in polynomial time

By definition, it solves the problem if it's capable of generating and verifying a solution on one of its tries

Example: CNF satisfiability

Problem: Is a boolean expression in its conjunctive normal form (CNF) satisfiable, i.e., are there values of its variables that makes it true? This problem is in  $NP$ .

Nondeterministic algorithm:

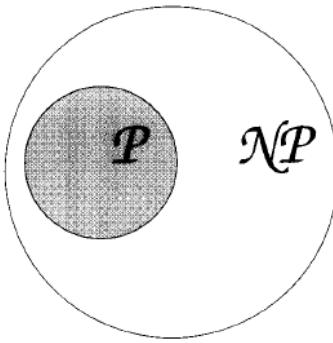
- Guess truth assignment
- Substitute the values into the CNF formula to see if it evaluates to true

### **What problems are in $NP$ ?**

- Hamiltonian circuit existence
- Partition problem: Is it possible to partition a set of  $n$  integers into two disjoint subsets with the same sum?
- Decision versions of TSP, knapsack problem, graph coloring, and many other combinatorial optimization problems. (Few exceptions include: MST, shortest paths)
- All the problems in  $P$  can also be solved in this manner (but no guessing is necessary), so we have:

$$P \subseteq NP$$

- Big question:  $P = NP$  ?



Commonly believed relationship between  $\mathcal{P}$  and  $\mathcal{NP}$

## NP HARD AND NP COMPLETE

### Polynomial Time algorithms

Problems whose solutions times are bounded by polynomials of small degree are called polynomial time algorithms

Example: Linear search, quick sort, all pairs shortest path etc.

### Non-Polynomial time algorithms

Problems whose solutions times are bounded by non-polynomials are called non-polynomial time algorithms

Examples: Travelling salesman problem, 0/1 knapsack problem etc

It is impossible to develop the algorithms whose time complexity is polynomial for non-polynomial time problems, because the computing times of non-polynomial are greater than polynomial. A problem that can be solved in polynomial time in one model can also be solved in polynomial time.

### NP-Hard and NP-Complete Problem:

Let  $P$  denote the set of all decision problems solvable by deterministic algorithm in polynomial time.  $NP$  denotes set of decision problems solvable by nondeterministic algorithms in polynomial time. Since, deterministic algorithms are a special case of nondeterministic algorithms,  $P \subseteq NP$ . The nondeterministic polynomial time problems can be classified into two classes. They are

1. NP Hard and
2. NP Complete

**NP-Hard:** A problem  $L$  is NP-Hard iff satisfiability reduces to  $L$  i.e., any nondeterministic polynomial time problem is satisfiable and reducible then the problem is said to be NP-Hard.

Example: Halting Problem, Flow shop scheduling problem

**NP-Complete:** A problem  $L$  is NP-Complete iff  $L$  is NP-Hard and  $L$  belongs to NP (nondeterministic polynomial).

A problem that is NP-Complete has the property that it can be solved in polynomial time iff all other NP-Complete problems can also be solved in polynomial time. ( $NP=P$ )

If an NP-hard problem can be solved in polynomial time, then all NP-complete problems can be solved in polynomial time. All NP-Complete problems are NP-hard, but some NP-hard problems are not known to be NP-Complete.

Normally the decision problems are NP-complete but the optimization problems are NP-Hard.

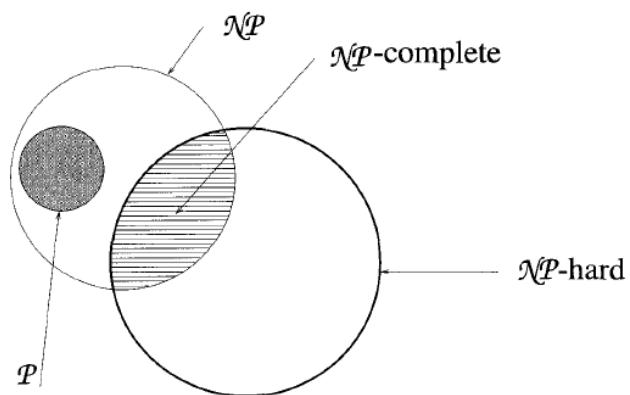
However if problem L1 is a decision problem and L2 is an optimization problem, then it is possible that  $L_1 \alpha L_2$ .

Example: Knapsack decision problem can be reduced to knapsack optimization problem.

There are some NP-hard problems that are not NP-Complete.

### Relationship between P,NP,NP-hard, NP-Complete

Let P, NP, NP-hard, NP-Complete are the sets of all possible decision problems that are solvable in polynomial time by using deterministic algorithms, non-deterministic algorithms, NP-Hard and NP-complete respectively. Then the relationship between P, NP, NP-hard, NP-Complete can be expressed using Venn diagram as:



Commonly believed relationship among  $P$ ,  $\mathcal{NP}$ ,  $\mathcal{NP}$ -complete, and  $\mathcal{NP}$ -hard problems

### Problem conversion

A decision problem D1 can be converted into a decision problem D2 if there is an algorithm which takes as input an arbitrary instance I1 of D1 and delivers as output an instance I2 of D2 such that I2 is a positive instance of D2 if and only if I1 is a positive instance of D1. If D1 can be converted into D2, and we have an algorithm which solves D2, then we thereby have an algorithm which solves D1. To solve an instance I of D1, we first use the conversion algorithm to generate an instance I0 of D2, and then use the algorithm for solving D2 to determine whether or not I0 is a positive instance of D2. If it is, then we know that I is a positive instance of D1, and if it is not, then we know that I is a negative instance of D1. Either way, we have solved D1 for that instance. Moreover, in this case, we can say that the computational complexity of D1 is at most the sum of the computational complexities of D2 and the conversion algorithm. If the conversion algorithm has polynomial complexity, we say that D1 is at most polynomially harder than D2. It means that the amount of computational work we have to do to solve D1, over and above whatever is required to solve D2, is polynomial in the size of the problem instance.

In such a case the conversion algorithm provides us with a feasible way of solving D1, given that we know how to solve D2.

Given a problem X, prove it is in NP-Complete.

1. Prove X is in NP.
2. Select problem Y that is known to be in NP-Complete.
3. Define a polynomial time reduction from Y to X.
4. Prove that given an instance of Y, Y has a solution iff X has a solution.

## Cook's theorem:

Cook's Theorem implies that any NP problem is at most polynomially harder than SAT. This means that if we find a way of solving SAT in polynomial time, we will then be in a position to solve any NP problem in polynomial time. This would have huge practical repercussions, since many frequently encountered problems which are so far believed to be intractable are NP. This special property of SAT is called NP-completeness. A decision problem is NP-complete if it has the property that any NP problem can be converted into it in polynomial time. SAT was the first NP-complete problem to be recognized as such (the theory of NP-completeness having come into existence with the proof of Cook's Theorem), but it is by no means the only one. There are now literally thousands of problems, cropping up in many different areas of computing, which have been proved to be NP-complete.

In order to prove that an NP problem is NP-complete, all that is needed is to show that SAT can be converted into it in polynomial time. The reason for this is that the sequential composition of two polynomial-time algorithms is itself a polynomial-time algorithm, since the sum of two polynomials is itself a polynomial.

Suppose SAT can be converted to problem D in polynomial time. Now take any NP problem D0. We know we can convert it into SAT in polynomial time, and we know we can convert SAT into D in polynomial time. The result of these two conversions is a polynomial-time conversion of D0 into

D. since D0 was an arbitrary NP problem, it follows that D is NP-complete