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Lecture Notes:

DESIGN AND ANALYSIS OF ALGORITHMS (ACSB13)

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Abbreviations

API	Application Program Interface
AIDC	Automatic Identification and Capture
BI	Business Intelligence
CDR	Call Detail Record Analysis
CEP	Complex Event Monitoring
CLASS	Comprehensive Large Array-Data Stewardship System
CMS	Content Management System
CRM	Customer Relationship Management
DAMA	Data Management Association
DBA	Database Administrator
DaaS	Database as a Service
DBMA	Database Management System
HER	Electronic Health Records
ERP	Enterprise Resource Planning
ETL	Extract, Transform, and Load
FISMA	Federal Information Security Management Act
HDF	Hadoop Distributed File System
HPC	High Performance Computing

Chapter 1

INTRODUCTION

Course Outcomes

After successful completion of this module, students should be able to:

CO 1	textbfFind running time and space complexity of given algorithms using techniques such as recurrences, potential functions, properties of probability.	Under-stand
CO 2	Apply divide and conquer algorithms for solving sorting, searching and matrix multiplication problems.	Under-stand

1.1 ALGORITHM

Algorithm was first time proposed a purshian mathematician Al-Chwarizmi in 825 AD. According to web star dictionary, algorithm is a special method to represent the procedure to solve given problem.

OR

An Algorithm is any well-defined computational procedure that takes some value or set of values as Input and produces a set of values or some value as output. Thus algorithm is a sequence of computational steps that transforms the input into the output.

Formal Definition

An Algorithm is a finite set of instructions that, if followed, accomplishes a particular task. In addition, all algorithms should satisfy the following criteria.

1. Input. Zero or more quantities are externally supplied.
2. Output. At least one quantity is produced.
3. Definiteness. Each instruction is clear and unambiguous.
4. Finiteness. If we trace out the instructions of an algorithm, then for all cases, the algorithm terminates after a finite number of steps.
5. Effectiveness. Every instruction must very basic so that it can be carried out, in principle, by a person using only pencil & paper.

Areas of study of Algorithm:

- How to device or design an algorithm– It includes the study of various design techniques and helps in writing algorithms using the existing design techniques like divide and conquer.
- How to validate an algorithm– After the algorithm is written it is necessary to check the correctness of the algorithm.i.e for each input correct output is produced, known as algorithm validation. The second phase is writing a program known as program proving or program verification.
- How to analysis an algorithm–It is known as analysis of algorithms or performance analysis, refers to the task of calculating time and space complexity of the algorithm.
- How to test a program – It consists of two phases . 1. debugging is detection and correction of errors. 2. Profiling or performance measurement is the actual amount of time required by the program to compute the result.

Algorithm Specification:

Algorithm can be described in three ways.

1. Natural language like English:
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 program, which resembles language like Pascal & algol

Pseudo-Code for writing Algorithms:

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>  
  
}
```

One step is a key word, other Step is used for increment or decrement.

repeat-until:

```
repeat{  
  
<statement-1> . . <statement-n>  
  
}until<condition>
```

8. A conditional statement has the following forms.

(1) If <condition> then <statement>

(2) If <condition> then <statement-1>

Else <statement-2>

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 list>)

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

Algorithm Max(A,n)

// A is an array of size n

{

Result := A[1];

for I:= 2 to n do

if A[I] > Result then

Result :=A[I];

return Result;

}

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

1.2 Performance Analysis

There are many Criteria to judge an algorithm.

- Is it correct?
- Is it readable?
- How it works

Performance evaluation can be divided into two major phases.

1. Performance Analysis (machine independent)

- space complexity: The space complexity of an algorithm is the amount of memory it needs to run for completion.
- time complexity: The time complexity of an algorithm is the amount of computer time it needs to run to completion.

2 .Performance Measurement (machine dependent).

Space Complexity:

The Space Complexity of any algorithm P is given by $S(P)=C+SP(I)$, C is constant.

1.Fixed Space Requirements (C)

Independent of the characteristics of the inputs and outputs – It includes instruction space
 – space for simple variables, fixed-size structured variable, constants

2. Variable Space Requirements ($SP(I)$)

depend on the instance characteristic I – number, size, values of inputs and outputs associated with I – recursive stack space, formal parameters, local variables, return address

Examples:

*Program 1 :Simple arithmetic function

Algorithmabc(a, b, c)

{

```
return a + b + b * c + (a + b - c) / (a + b) + 4.00;

}
```

SP(I)=0

HenceS(P)=Constant

Program 2: Iterative function for sum a list of numbers

Algorithm sum(list[], n)

```
{

tempsum = 0;

for i = 0 ton do

tempsum += list [i];

return tempsum;

}
```

In the above example list[] is dependent on n. Hence SP(I)=n. The remaining variables are i,n, tempsum each requires one location.

Hence S(P)=3+n

*Program 3: Recursive function for sum a list of numbers

Algorithmrsum(list[], n)

```
{

If (n<=0) then

return 0.0

else

return rsum(list, n-1) + list[n];

}
```

In the above example the recursion stack space includes space for formal parameters local variables and return address. Each call to rsum requires 3 locations i.e for list[],n and return address .As the length of recursion is n+1.

$$S(P) \geq 3(n+1)$$

1.2.1 Time complexity

$$T(P) = C + TP(I)$$

It is combination of-Compile time (C)

independent of instance characteristics

-run (execution) time TP

dependent of instance characteristics

Time complexity is calculated in terms of program step as it is difficult to know the complexities of individual operations.

Definition: A program step is a syntactically or semantically meaningful program segment whose execution time is independent of the instance characteristics. Program steps are considered for different statements as : for comment zero steps . assignment statement is considered as one step. Iterative statements such as “for, while and until-repeat” statements, we consider the step counts based on the expression .

Methods to compute the step count: 1) Introduce variable count into programs 2) Tabular method – Determine the total number of steps contributed by each statement step per execution frequency – add up the contribution of all statements

Program 1.with count statements

Algorithm sum(list[], n)

{

tempsum:= 0; count++; /* for assignment */

for i := 1 to n do{

```

count++; /*for the for loop */

tempsum :=tempsum + list[i]; count++; /* for assignment */

}

count++; /* last execution of for */

return tempsum;

count++; /* for return */

```

Hence $T(n)=2n+3$

Program :Recursive sum

```

Algorithmrsum( list[ ], n)

{ count++; /*for if conditional */

if (n<=0)

{ count++; /* for return */

return 0.0 }

else

returnrsum(list, n-1) + list[n];

count++;/*for return and rsum invocation*/

}

```

$T(n)=2n+2$

Program for matrix addition

```

Algorithm add( a[ ][MAX_SIZE], b[ ][MAX_SIZE],

c[ ][MAX_SIZE], rows, cols )

{

```

```

for i := 1 to rows do
{
count++; /* for i for loop */

for j := 1 to cols do {

count++; /* for j for loop */

c[i][j] := a[i][j] + b[i][j];

count++; /* for assignment statement */

}

count++; /* last time of j for loop */

}

count++; /* last time of i for loop */

}

T(n)=2rows*cols+2*rows+1

```

II Tabular method.

Complexity is determined by using a table which includes steps per execution(s/e) i.e amount by which count changes as a result of execution of the statement. Frequency – number of times a statement is executed.

1.3 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 bestcase.
2. Average Case : The average value of $f(n)$.
3. Worst Case : The maximum value of $f(n)$ for any key possible input.

The field of computer science, which studies efficiency of algorithms, is known as analysis of algorithms.

Algorithms can be evaluated by a variety of criteria. Most often we shall be interested in the rate of growth of the time or space required to solve larger and larger instances of a problem. We will associate with the problem an integer, called the size of the problem, which is a measure of the quantity of input data. Rate of Growth:

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

Asymptotic notation

Big oh notation: O

The function $f(n) = O(g(n))$ (read as “ f of n is big oh of g of n ”) iff there exist positive constants c and n_0 such that $f(n) \leq c \cdot g(n)$ for all $n, n \geq n_0$

The value $g(n)$ is the upper bound value of $f(n)$.

Example:

$3n+2 = O(n)$ as

$3n+2 \leq 4n$ for all $n \geq 2$

Omega notation: Ω

The function $f(n) = \Omega(g(n))$ (read as “ f of n is Omega of g of n ”) iff there exist positive constants c and n_0 such that $f(n) \geq c \cdot g(n)$ for all $n, n \geq n_0$

The value $g(n)$ is the lower bound value of $f(n)$.

Example:

$3n+2 = \Omega(n)$ as

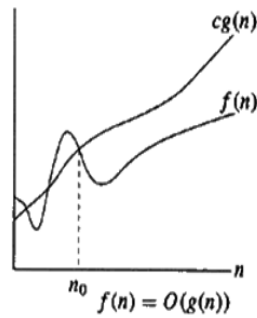


Figure 1.1: Asymptotic notation

$3n+2 \leq 3n$ for all $n \geq 1$

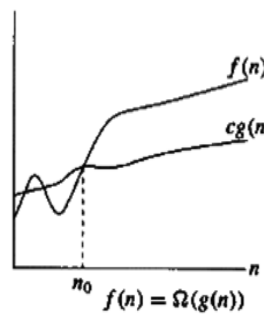


Figure 1.2: Omega notation

Theta notation:

The function $f(n) = \Theta(g(n))$ (read as “f of n is theta of g of n”) iff there exist positive constants c_1 , c_2 and n_0 such that $c_1 \cdot g(n) \leq f(n) \leq c_2 \cdot g(n)$ for all $n, n \geq n_0$

Example:

$3n+2 = \Theta(n)$ as

$3n+2 \leq 3n$ for all $n \geq 2$

$3n+2 \geq 3n$ for all $n \geq 2$

Here $c_1=3$ and $c_2=4$ and $n_0=2$

Little oh: o

The function $f(n) = o(g(n))$ (read as “f of n is little oh of g of n”) iff

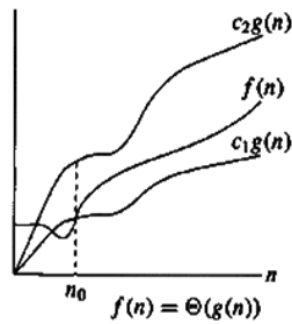


Figure 1.3: Omega notation

$\lim_{n \rightarrow \infty} f(n)/g(n) = 0$ for all $n, n > 0$

n

Example:

$3n+2 = o(n^2)$ as

$\lim_{n \rightarrow \infty} ((3n+2)/n^2) = 0$

n

Little Omega:

The function $f(n) = \omega(g(n))$ (read as “f of n is little ohomega of g of n”) iff

$\lim_{n \rightarrow \infty} g(n)/f(n) = 0$ for all $n, n > 0$

n

Example:

$3n+2 = o(n^2)$ as

$\lim_{n \rightarrow \infty} (n^2/(3n+2)) = \infty$

n

1.4 Analyzing Algorithms

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:

$O(1)$, $O(\log 2n)$, $O(n)$, $O(n \cdot \log 2n)$, $O(n^2)$, $O(n^3)$, $O(2n)$, $n!$ and n^n

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

Note 2: The value here is about 500 billion times the age of the universe in nanoseconds, assuming a universe age of 20 billion years.

Graph of $\log n$, n , $n \log n$, n^2 , n^3 , $2n$, $n!$ and n^n

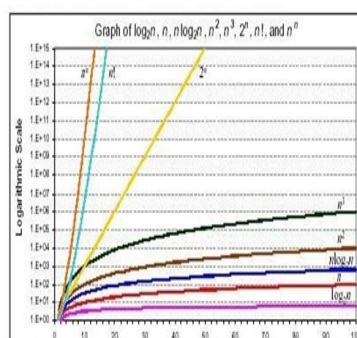


Figure 1.4: Analyzing Algorithms

One way to compare the function $f(n)$ with these standard function is to use the functional ‘O’ notation, suppose $f(n)$ and $g(n)$ are functions defined on the positive integers with the property that $f(n)$ is bounded by some multiple $g(n)$ for almost all ‘n’. Then, $f(n) = O(g(n))$

Which is read as “ $f(n)$ is of order $g(n)$ ”. For example, the order of complexity for:

- Linear search is $O(n)$
- Binary search is $O(\log n)$
- Bubble sort is $O(n^2)$
- Merge sort is $O(n \log n)$

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 a known algorithm.

1.5 DIVIDE AND CONQUER

General method:

Given a function to compute on 'n' inputs the divide-and-conquer strategy suggests splitting the inputs into 'k' distinct subsets, $1 < k \leq n$, yielding 'k' sub problems. These sub problems must be solved, and then a method must be found to combine sub solutions into a solution of the whole.

If the sub problems are still relatively large, then the divide-and-conquer strategy can possibly be reapplied. Often the sub problems resulting from a divide-and-conquer design are of the same type as the original problem. For those cases the re application of the divide-and-conquer principle is naturally expressed by a recursive algorithm. DAndC(Algorithm) is initially invoked as DandC(P), where 'p' is the problem to be solved. Small(P) is a Boolean-valued function that determines whether the i/p size is small enough that the answer can be computed without splitting. If this so, the function 'S' is invoked. Otherwise, the problem P is divided into smaller sub problems. These sub problems P1, P2 ...Pk are solved by recursive application of DAndC. Combine is a function that determines the solution to p using the solutions to the 'k' sub problems. If the size of 'p' is n and the sizes of the 'k' sub problems are n1, n2nk, respectively, then the computing time of DAndC is described by the recurrence relation.

$$T(n) = \begin{cases} g(n) & n \text{ small} \\ T(n_1) + T(n_2) + \dots + T(n_k) + f(n); & \text{otherwise.} \end{cases}$$

$$T(n_1) + T(n_2) + \dots + T(n_k) + f(n); \text{ otherwise.}$$

Where T(n) is the time for DAndC on any i/p of size 'n'.

g(n) is the time of compute the answer directly for small i/ps.

f(n) is the time for dividing P & combining the solution to

sub problems.

Algorithm 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));

}

}
```

The complexity of many divide-and-conquer algorithms is given by recurrence relation of the form $T(n) = T(1)$

$$= aT(n/b) + f(n) \quad n > 1$$

Where a & b are known constants.

We assume that $T(1)$ is known & 'n' is a power of b (i.e., $n = bk$)

One of the methods for solving any such recurrence relation is called the substitution method. This method repeatedly makes substitution for each occurrence of the function. T is the right-hand side until all such occurrences disappear.

Example:

1) Consider the case in which $a=2$ and $b=2$. Let $T(1)=2$ & $f(n)=n$.

We have,

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

$$= 2[2T(n/2/2)+n/2]+n$$

$$= [4T(n/4)+n]+n$$

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

$$= 4[2T(n/4/2)+n/4]+2n$$

$$= 4[2T(n/8)+n/4]+2n$$

$$= 8T(n/8)+n+2n$$

$$= 8T(n/8)+3n$$

*

*

- In general, we see that $T(n)=2^i T(n/2^i)+in.$, for any $\log_2 n \geq i \geq 1$.

$$T(n) = 2^{\log_2 n} T(n/2^{\log_2 n}) + n \log_2 n$$

Corresponding to the choice of $i=\log_2 n$

$$\text{Thus, } T(n) = 2^{\log_2 n} T(n/2^{\log_2 n}) + n \log_2 n$$

$$= n. T(n/n) + n \log_2 n$$

$$= n. T(1) + n \log_2 n \text{ [since, } \log_2 1=0, 2^0=1]$$

$$= 2n + n \log_2 n$$

$$T(n) = n \log_2 n + 2n.$$

The recurrence using the substitution method, it can be shown as

$$T(n) = n \log_2 a [T(1) + u(n)]$$

Applications of Divide and conquer rule or algorithm:

Binary search, Quick sort, Merge sort, Strassen's matrix multiplication.

1.5.1 Binary search

Given a list of n elements arranged in increasing order. The problem is to determine whether a given element is present in the list or not. If x is present then determine the position of x , otherwise position is zero.

Divide and conquer is used to solve the problem. The value $\text{Small}(p)$ is true if $n=1$. $S(P)=i$, if $x=a[i]$, $a[]$ is an array otherwise $S(P)=0$. If P has more than one element then it can be divided into sub-problems. Choose an index j and compare x with $a[j]$. then there 3 possibilities (i). $x=a[j]$ (ii) $x < a[j]$ (x is searched in the list $a[1] \dots a[j-1]$) (iii) $x > a[j]$ (x is searched in the list $a[j+1] \dots a[n]$).

And the same procedure is applied repeatedly until the solution is found or solution is zero.

Algorithm Binsearch(a, n, x)

// Given an array $a[1:n]$ of elements in non-decreasing

//order, $n \geq 0$, determine whether ' x ' is present and

// if so, return ' j ' such that $x=a[j]$; else return 0.

{

low:=1; high:=n;

while (low<=high) do

{

mid:=[(low+high)/2];

if ($x < a[\text{mid}]$) then high;

else if ($x > a[\text{mid}]$) then

low:=mid+1;

else return mid;


```

}

return 0;

}

```

Algorithm, describes this binary search method, where Binsrch has 4 inputs $a[], l, n, x$. It is initially invoked as $\text{Binsrch}(a, l, n, x)$. A non-recursive version of Binsrch is given below.

This Binsearch has 3 inputs $a[], l, n, x$. The while loop continues processing as long as there are more elements left to check. At the conclusion of the procedure 0 is returned if x is not present, or 'j' is returned, such that $a[j] = x$. We observe that low & 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 at least one.

Thus we have 2 sequences of integers approaching each other and eventually low becomes $>$ than high causes termination in a finite no. of steps if ' x ' is not present.

Example:

1) Let us select the 14 entries.

-15, -6, 0, 7, 9, 23, 54, 82, 101, 112, 125, 131, 142, 151.

Place them in $a[1:14]$, and simulate the steps Binsearch goes through as it searches for different values of ' x '.

Only the variables, low, high & mid need to be traced as we simulate the algorithm. We try the following values for x : 151, -14 and 9.

for 2 successful searches & 1 unsuccessful search.

Theorem: Algorithm $\text{Binsearch}(a, n, x)$ works correctly.

Proof: We assume that all statements work as expected and that comparisons such as $x > a[mid]$ are appropriately carried out.

Initially $low = 1$, $high = n$, $n > 0$, and $a[1] \leq a[2] \leq \dots \leq a[n]$.

If $n = 0$, the while loop is not entered and 0 is returned. Otherwise we observe that each time thro' the loop the possible elements to be checked of or equality with x and $a[low]$,

$a[\text{low}+1], \dots, a[\text{mid}], \dots, a[\text{high}]$. If $x = a[\text{mid}]$, then the algorithm terminates successfully. Otherwise, the range is narrowed by either increasing low to $(\text{mid}+1)$ or decreasing high to $(\text{mid}-1)$. Clearly, this narrowing of the range does not affect the outcome of the search. If low becomes $>$ than high, then 'x' is not present & hence the loop is exited.

The complexity of binary search in successful searches is

Worst case is $O(\log n)$ or $(\log n)$

Average case is $O(\log n)$ or $(\log n)$

Best case is $O(1)$ or (1)

1.5.2 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 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 highdo
    {
      b[i] := a[k]; i := i + 1
    }
  for k := h to middo
    {
      b[i] := a[k]; i := i + 1;
    }
  for k := low to highdo
    a[k] := b[k];
  }

```

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 $n = 2k$.

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:

$$T(1) = 1$$

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

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

1.6 Strassen's Matrix Multiplication

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

Let A and B be two $n \times n$ Matrices. The product matrix $C=AB$ is also a $n \times n$ matrix whose i, j th element is formed by taking elements in the i th row of A and j th column of B and multiplying them to get

Here $1 \leq i \leq n$ & $1 \leq j \leq n$ means i and j are in between 1 and n .

To compute $C(i, j)$ using this formula, we need n multiplications.

The divide and conquer strategy suggests another way to compute the product of two $n \times n$ matrices. For Simplicity assume n is a power of 2 that is $n=2^k$, k is a nonnegative integer.

If n is not power of two then enough rows and columns of zeros can be added to both A and B, so that resulting dimensions are a power of two.

To multiply two $n \times n$ matrices A and B, yielding result matrix 'C' as follows: Let A and B be two $n \times n$ Matrices. Imagine that A & B are each partitioned into four square sub matrices. Each sub matrix having dimensions $n/2 \times n/2$.

The product of AB can be computed by using previous formula.

1.7 Quick Sort

The main reason for the slowness of Algorithms in which 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 has devised a very efficient way of implementing this idea in the early 1960's that improves the $O(n^2)$ behavior of the 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 $\text{low} \geq \text{high}$ is satisfied. This condition will be satisfied only when the array is completely sorted. Here we choose the first element as the 'pivot'. So, $\text{pivot} = x[\text{low}]$. Now it calls the partition function to find the proper position j of the element $x[\text{low}]$ i.e. pivot. Then we will have two sub-arrays $x[\text{low}]$, $x[\text{low}+1]$, $x[j-1]$ and $x[j+1]$, $x[j+2]$, . . . $x[\text{high}]$. It calls itself recursively to sort the left sub-array $x[\text{low}]$, $x[\text{low}+1]$, $x[j-1]$ between positions low and j-1 (where j is returned by the partition function). It calls itself recursively to sort the right sub-array $x[j+1]$, $x[j+2]$, $x[\text{high}]$ between positions j+1 and high.

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 quicksort:

Analysis of QuickSort:

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. 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:

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

Where, $i = |S1|$ is the number of elements in $S1$.

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:

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

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

$$= O(n^2)$$

Best Case Analysis

In the best case, the pivot is in the middle. To simplify the math, we assume that the two sub-files are each exactly half the size of the original and although this gives a slight over estimate, this is acceptable because we are only interested in a Big – oh answer.

$$T(n) = 2 T(n/2) + Cn \quad (4)$$

Divide both sides by n and Substitute $n/2$ for ' n '

Finally,

Which yields, $T(n) = C n \log n + n = O(n \log n)$ -

This is exactly the same analysis as merge sort, hence we get the same answer.

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

Chapter 2

SEARCHING AND TRAVERSAL TECHNIQUES

Course Outcomes

After successful completion of this module, students should be able to:

CO 5	Find running time and space complexity of given algorithms using techniques such as recurrences, potential functions, properties of probability.	Analyze
CO 6	Apply divide and conquer algorithms for solving sorting, searching and matrix multiplication problems.	Under-stand

2.1 Disjoint Set Operations

Set:

A set is a collection of distinct elements. The Set can be represented,for examples, as $S1=\{1,2,5,10\}$.

Disjoint Sets:

The disjoint sets are those do not have any common element.

For example $S1=\{1,7,8,9\}$ and $S2=\{2,5,10\}$, then we can say that $S1$ and $S2$ are two disjoint sets.

Disjoint Set Operations:

The disjoint set operations are

1. Union

2. Find

Disjoint set Union:

If S_i and S_j are two disjoint sets, then their union $S_i \cup S_j$ consists of all the elements x such that x is in S_i or S_j .

Find:

Example:

$S1=\{1,7,8,9\}$ $S2=\{2,5,10\}$

$S1 \cup S2=\{1,2,5,7,8,9,10\}$

Given the element I , find the set containing I .

2.1.1 Set Representation

The set will be represented as the tree structure where all children will store the address of parent / root node. The root node will store null at the place of parent address. In the given set of elements any element can be selected as the root node, generally we select the first node as the root node.

Example:

$S1=\{1,7,8,9\}$ $S2=\{2,5,10\}$ $s3=\{3,4,6\}$

Then these sets can be represented as

Disjoint Union:

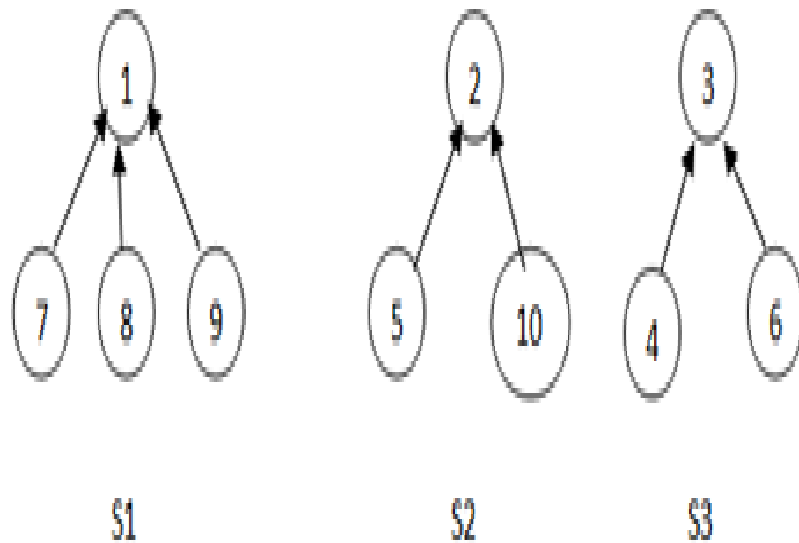


Figure 2.1: Set Representation 1

To perform disjoint set union between two sets S_i and S_j can take any one root and make it sub-tree of the other. Consider the above example sets S_1 and S_2 then the union of S_1 and S_2 can be represented as any one of the following.

Find:

To perform find operation, along with the tree structure we need to maintain the name of each set. So, we require one more data structure to store the set names. The data structure contains two fields. One is the set name and the other one is the pointer to root.

Union and Find Algorithms:

In presenting Union and Find algorithms, we ignore the set names and identify sets just by the roots of trees representing them. To represent the sets, we use an array of 1 to n elements where n is the maximum value among the elements of all sets. The index values represent the nodes (elements of set) and the entries represent the parent node. For the root value the entry will be '-1'.

Example:

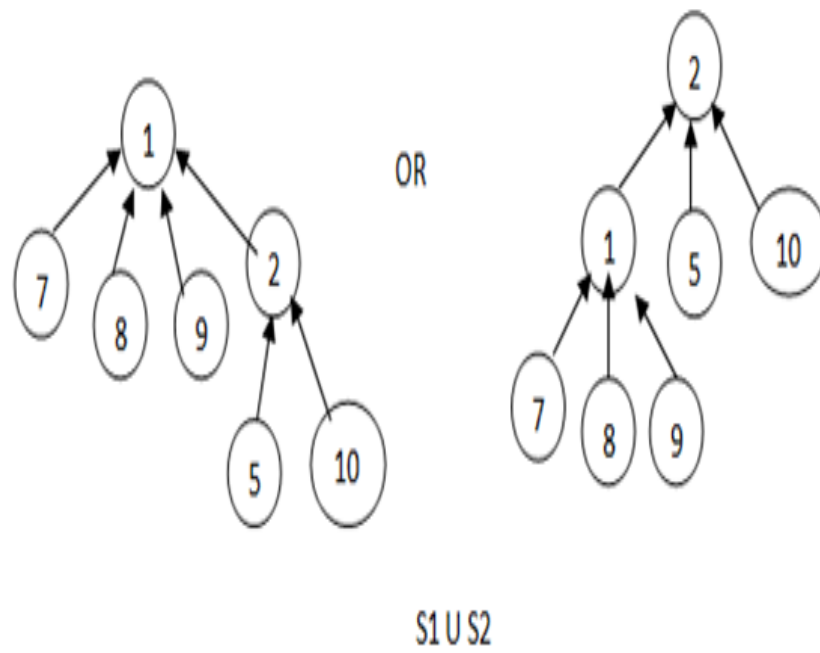


Figure 2.2: Set Representation 1

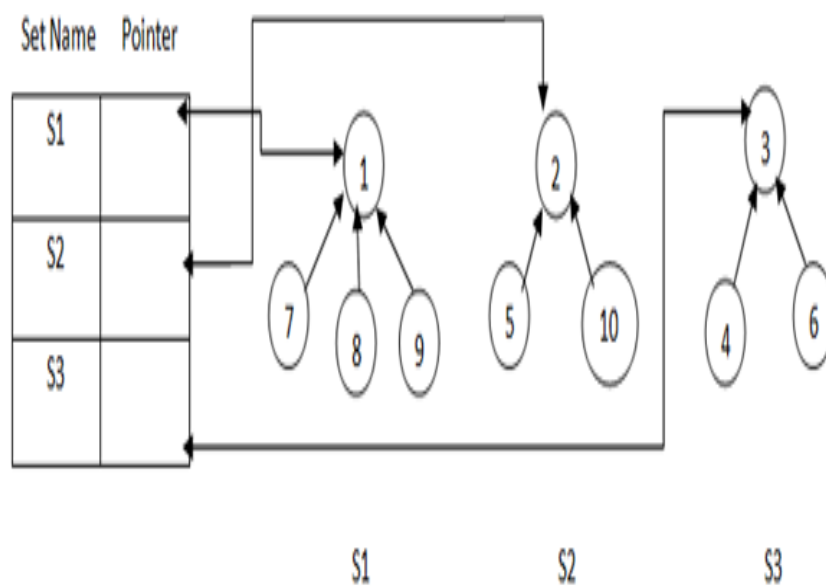


Figure 2.3: Set Representation 1

For the following sets the array representation is as shown below.

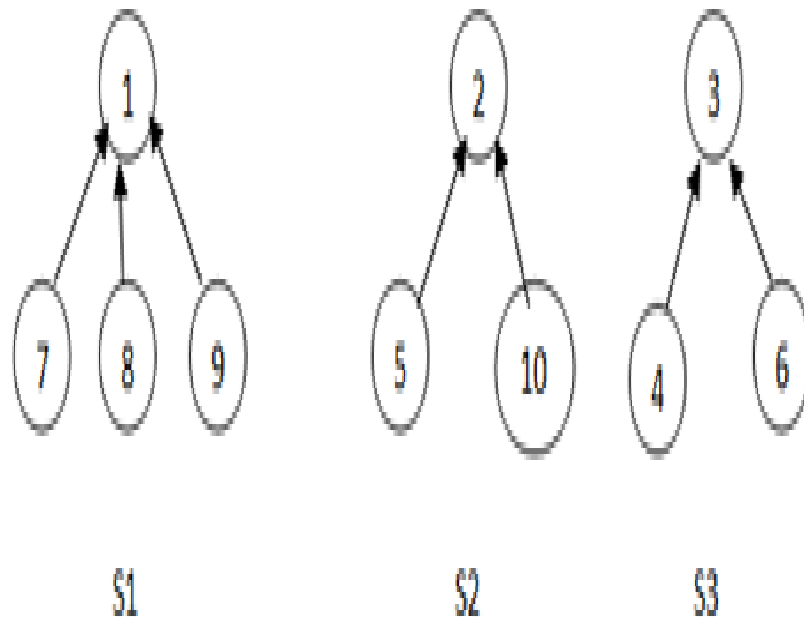


Figure 2.4: Union and Find Algorithms

Algorithm for Union operation:

To perform union the SimpleUnion(i, j) function takes the inputs as the set roots i and j . And make the parent of i as j i.e, make the second root as the parent of first root.

Algorithm SimpleUnion(i, j)

```
{
P[i]:=j;
}
```

Algorithm for find operation:

The SimpleFind(i) algorithm takes the element i and finds the root node of i . It starts at i until it reaches a node with parent value-1.

Algorithm SimpleFind(i)

```

{
while( P[i] 0)

i:=P[i];

returni; }

```

Analysis of SimpleUnion(i,j) and SimpleFind(i):

Although the SimpleUnion(i,j) and SimpleFind(i) algorithms are easy to state, their performance characteristics are not very good. For example, consider the sets

Then if we want to perform following sequence of operations Union(1,2) ,Union(2,3)..... Union(n-1,n) and sequence of Find(1), Find(2).....Find(n).

The sequence of Union operations results the degenerate tree as below.

Since, the time taken for a Union is constant, the n-1 sequence of union can be processed in time $O(n)$. And for the sequence of Find operations it will take We can improve the performance of union and find by avoiding the creation of degenerate tree by applying weighting rule for Union.

Weighting rule for Union:

If the number of nodes in the tree with root i is less than the number in the tree with the root j, then make 'j' the parent of i; otherwise make 'i' the parent of j.

To implement weighting rule we need to know how many nodes are there in every tree. To do this we maintain "count" field in the root of every tree. If 'i' is the root then count[i] equals to number of nodes in tree with root i. Since all nodes other than roots have positive numbers in parent (P) field, we can maintain count in P field of the root as negative number.

Algorithm WeightedUnion(i,j)

```

//Union sets with roots i and j, i j using the weighted rule

// P[i]=-count[i] and p[j]=-count[j]

{

```

```

temp:=P[i]+P[j];

if (P[i]>P[j])then

{

// i has fewer nodes P[i]:=j;

P[j]:=temp;

}

else

{

// j has fewer nodes P[j]:=i;

}

}

```

Collapsing rule for find:

If j is a node on the path from i to its root and $p[i]$ root $[i]$, then set $P[j]$ to root $[i]$. Consider the tree created by `WeightedUnion()` on the sequence of 1 to 8. `Union(1,2)`, `Union(3,4)`, `Union(5,6)` and `Union(7,8)`

Now process the following eight find operations `Find(8), Find(8),`

`Find(8)` If `SimpleFind()` is used each `Find(8)` requires going up three parent link fields for a total of 24 moves.

When Collapsing find is used the first `Find(8)` requires going up three links and resetting three links. Each of remaining seven finds require going up only one link field. Then the total cost is now only 13 moves. (3 going up + 3 resets + 7 remaining finds).

Algorithm `CollapsingFind(i)`

```

// Find the root of the tree containing element i. Use the

// collapsing rule to collapse all nodes from i to the root.

```

```
{ r := i;

while(p[r] > 0) do

r := p[r]; / Find the root,

while (i < r) do // Collapse nodes from i to root r,

r:=p[i];

returnr;

}
```

2.2 SEARCHING

Search means finding a path or traversal between a start node and one of a set of goal nodes. Search is a study of states and their transitions.

Search involves visiting nodes in a graph in a systematic manner, and may or may not result into a visit to all nodes. When the search necessarily involved the examination of every vertex in the tree, it is called the traversal.

Techniques for Traversal of a Binary Tree:

A binary tree is a finite (possibly empty) collection of elements. When the binary tree is not empty, it has a root element and remaining elements (if any) are partitioned into two binary trees, which are called the left and right subtrees.

There are three common ways to traverse a binary tree: Preorder, Inorder, postorder

In all the three traversal methods, the left sub tree of a node is traversed before the right sub tree. The difference among the three orders comes from the difference in the time at which a node is visited.

2.2.1 Inorder Traversal

In the case of inorder traversal, the root of each subtree is visited after its left subtree has been traversed but before the traversal of its right subtree begins. The steps for traversing a binary tree in inorder traversal are:

1. Visit the left subtree, using inorder.
2. Visit the root.
3. Visit the right subtree, using inorder.

The algorithm for preorder traversal is as follows:

```
treenode = record
```

```
{
```

```
Type data; //Type is the data type of data.
```

```
Treenode *lchild, *rchild;
```

```
}
```

```
Algorithm inorder(t)
```

```
// t is a binary tree. Each node of t has three fields: lchild, data, and rchild.
```

```
{
```

```
If( t != 0)then
```

```
{
```

```
inorder (t->lchild); visit(t);
```

```
inorder (t ->rchild);
```

```
}
```

```
}
```

2.2.2 Preorder Traversal

In a preorder traversal, each node is visited before its left and right subtrees are traversed. Preorder search is also called backtracking. The steps for traversing a binary tree in preorder traversal are:

1. Visit the root.
2. Visit the left subtree, using preorder.
3. Visit the right subtree, using preorder.

The algorithm for preorder traversal is as follows:

Algorithm Preorder (t)

// t is a binary tree. Each node of t has three fields; lchild, data, and rchild. {

If(t \neq 0)then

{

Preorder (t \rightarrow lchild); Preorder (t \rightarrow rchild);

}

}

2.2.3 Postorder Traversal

In a Postorder traversal, each root is visited after its left and right subtrees have been traversed. The steps for traversing a binary tree in postorder traversal are:

1. Visit the left subtree, using postorder.
2. Visit the right subtree, using postorder
3. Visit the root

The algorithm for preorder traversal is as follows:

Algorithm Postorder (t)

// t is a binary tree. Each node of t has three fields :lchild, data, and rchild.

```
{
If( t != 0)then
{
Postorder(t->lchild); Postorder(t->rchild); visit(t);
} }
```

Examples for binary tree traversal/search technique:

2.3 Non Recursive Binary Tree Traversal Algorithms

At first glance, it appears we would always want to use the flat traversal functions since they use less stack space. But the flat versions are not necessarily better. For instance, some overhead is associated with the use of an explicit stack, which may negate the savings we gain from storing only node pointers. Use of the implicit function call stack may actually be faster due to special machine instructions that can be used.

2.3.1 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

}

}

```

2.3.2 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 != 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
}
}
```

2.3.3 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 $-(\text{right son of vertex})$ 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  $\neq$  0)

{

push vertex onto stack if(rightson(vertex)  $\neq$  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

}

}
```

2.3.4 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.

2.3.5 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.

2.3.6 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.

2.4 Subgraphs and Spanning Trees

Subgraphs: A graph $G' = (V', E')$ is a subgraph of graph $G = (V, E)$ iff $V' \subseteq V$ and

$E' \subseteq E$.

E .

The undirected graph G is connected, if for every pair of vertices u, v there exists a path from u to v . If a graph is not connected, the vertices of the graph can be divided into connected components. Two vertices are in the same connected component iff they are connected by a path.

Tree is a connected acyclic graph. A spanning tree of a graph $G = (V, E)$ is a tree that contains all vertices of V and is a subgraph of G . A single graph can have multiple spanning trees.

Lemma 1: Let T be a spanning tree of a graph G . Then

1. Any two vertices in T are connected by a unique simple path.
2. If any edge is removed from T , then T becomes disconnected.
3. If we add any edge into T , then the new graph will contain a cycle.
4. Number of edges in T is $n-1$.

2.5 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.

Examples:

To explain the Minimum Spanning Tree, let's consider a few 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.

2.6 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.

Algorithm:

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; $j := \text{Find}(u)$; $k := \text{Find}(v)$; if $(j \neq k)$ 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;

}

```

2.7 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

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.

2.8 MINIMUM-COST SPANNING TREES

:

2.8.1 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.

```
// 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 ∞ 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 fort.

{

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;

}

```

Running time:

We do the same set of operations with dist as in Dijkstra's algorithm (initialize structure, m times decrease value, $n - 1$ times select minimum). Therefore, we get $O(n^2)$ time when we implement dist with array, $O(n + E \log n)$ when we implement it with a heap.

For each vertex u in the graph we dequeue it and check all its neighbors in $O(1 + \deg(u))$ time.

2.9 GRAPH ALGORITHMS

Basic Definitions:

- Graph G is a pair (V, E) , where V is a finite set (set of vertices) and E is a finite set of pairs from V (set of edges). We will often denote $n := |V|$, $m := |E|$.
- Graph G can be directed, if E consists of ordered pairs, or undirected, if E consists of unordered pairs. If $(u, v) \in E$, then vertices u , and v are adjacent.

- We can assign weight function to the edges: $w_G(e)$ is a weight of edge $e \in E$. The graph which has such function assigned is called weighted graph.
- Degree of a vertex v is the number of vertices u for which $(u, v) \in E$ (denote $\deg(v)$). The number of incoming edges to a vertex v is called in-degree of the vertex (denote $\text{indeg}(v)$). The number of outgoing edges from a vertex is called out-degree (denote $\text{outdeg}(v)$).

Representation of Graphs:

Consider graph $G = (V, E)$, where $V = \{v_1, v_2, \dots, v_n\}$.

Adjacency matrix represents the graph as an $n \times n$ matrix $A = (a_{ij})$, where

The matrix is symmetric in case of undirected graph, while it may be asymmetric if the graph is directed.

We may consider various modifications. For example for weighted graphs, we may have

Where default is some sensible value based on the meaning of the weight function (for example, if weight function represents length, then default can be ∞ , meaning value larger than any other value).

Adjacency List: An array $\text{Adj} [1 \dots n]$ of pointers where for $1 < v < n$, $\text{Adj} [v]$ points to a linked list containing the vertices which are adjacent to v (i.e. the vertices that can be reached from v by a single edge). If the edges have weights then these weights may also be stored in the linked list elements.

2.10 Paths and Cycles

A path is a sequence of vertices (v_1, v_2, \dots, v_k) , where for all i , $(v_i, v_{i+1}) \in E$. A path is simple if all vertices in the path are distinct.

A (simple) cycle is a sequence of vertices $(v_1, v_2, \dots, v_k, v_{k+1} = v_1)$, where for all i , $(v_i, v_{i+1}) \in E$ and all vertices in the cycle are distinct except pair v_1, v_{k+1} .

Techniques for graphs:

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

Connected Component:

Connected component of a graph can be obtained by using BFST (Breadth first search and traversal) and DFST (Depth first search and traversal). It is also called the spanning tree.

2.10.1 BFST (Breadth first search and traversal)

In BFS we start at a vertex V mark it as reached (visited). The vertex V is at this time said to be unexplored (not yet discovered). A vertex is said to be explored (discovered) by visiting all vertices adjacent from it. All unvisited vertices adjacent from V are visited next. The first vertex on this list is the next to be explored. Exploration continues until no unexplored vertex is left. These operations can be performed by using Queue.

This is also called connected graph or spanning tree. Spanning trees obtained using BFS then it called breadth first spanning trees

Algorithm BFS(v)

```
// a bfs of G is begin at vertex v

// for any node I, visited[i]=1 if I has already been visited.

// the graph G, and array visited[] are global

{

U:=v; // q is a queue of unexplored vertices.

Visited[v]:=1;

Repeat{

For all vertices w adjacent from U do

If (visited[w]=0) then
```

```

{
Add w to q; // w is unexplored

Visited[w]:=1;

}

If q is empty then return; // No unexplored vertex.

Delete U from q; //Get 1st unexplored vertex.

} Until(false)

}

```

Maximum Time complexity and space complexity of $G(n,e)$, nodes are in adjacency list.

$$T(n, e) = (n+e)$$

$$S(n, e) = (n)$$

If nodes are in adjacency matrix then

$$T(n, e) = (n^2)$$

$$S(n, e) = (n)$$

2.10.2 DFST(Dept first search and traversal)

DFS different from BFS. The exploration of a vertex v is suspended (stopped) as soon as a new vertex is reached. In this the exploration of the new vertex (example v) begins; this new vertex has been explored, the exploration of v continues. Note: exploration start at the new vertex which is not visited in other vertex exploring and choose nearest path for exploring next or adjacent vertex.

Algorithm dFS(v)

// a Dfs of G is begin at vertex v

// initially an array visited[] is set to zero.

```
//this algorithm visits all vertices reachable from v.

// the graph G, and array visited[] are global
```

2.11 Bi-connected Components

A graph G is biconnected, iff (if and only if) it contains no articulation point (joint or junction). A vertex v in a connected graph G is an articulation point, if and only if (iff) the deletion of vertex v together with all edges incident to v disconnects the graph into two or more non empty components. The presence of articulation points in a connected graph can be an undesirable (un wanted) feature in many cases. For example if G is a Communication network with Vertex communication stations. Edges Communication lines.

Then the failure of a communication station v that is an articulation point, then we lose the communication in between other stations. F

Form graph G

```
{
Visited[v]:=1;

For each vertex w adjacent from v do
{
If (visited[w]=0) then DFS(w);
{
Add w to q; // w is unexplored

Visited[w]:=1;
}
}
}
```

Maximum Time complexity and space complexity of $G(n,e)$, nodes are in adjacency list.

$$T(n, e) = (n+e)$$

$$S(n, e) = (n)$$

If nodes are in adjacency matrix then

$$T(n, e) = (n^2)$$

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2.12 Bi-connected Components

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The presence of articulation points in a connected graph can be an undesirable(un wanted) feature in many cases.

For example

if G_1 Communication network with

Vertex communication stations.

Edges Communication lines.

Then the failure of a communication station I that is an articulation point, then we loss the communication in between other stations. F

Form graph G_1

There is an efficient algorithm to test whether a connected graph is biconnected. If the case of graphs that are not biconnected, this algorithm will identify all the articulation points.

Once it has been determined that a connected graph G is not biconnected, it may be desirable (suitable) to determine a set of edges whose inclusion makes the graph biconnected.

Chapter 3

GREEDY METHOD AND DYNAMIC PROGRAMMING

Course Outcomes

After successful completion of this module, students should be able to:

CO 6	Find running time and space complexity of given algorithms using techniques such as recurrences, potential functions, properties of probability.	Understand
CO 7	Apply divide and conquer algorithms for solving sorting, searching and matrix multiplication problems..	Apply

3.1 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.

CONTROLABSTRACTION Algorithm Greedy (a,n)

```
// a(1 : n) contains the 'n' inputs
```

```
{
```

```
  solution:= ; // initialize the solution to be empty
```

```
  for i:=1 to ndo
```

```
  {
```

```
    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.

3.2 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:

The profits and weights are positive numbers.

Algorithm

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 the solution vector 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:
2. Select the object with the maximum profit first ($p = 25$). So, $x_1 = 1$ and profit earned is 25. Now, only 2 Modules of space is left, select the object with next largest profit ($p = 24$). So, $x_2 = 2/15$
3. Considering the objects in the order of non-decreasing weights w_i .
4. Considered the objects in the order of the ratio p_i / w_i .

Sort the objects in order of the non-increasing order of the ratio p_i / w_i . Select the object with the maximum p_i / w_i ratio, so, $x_1 = 1$ and profit earned is 24. Now, only 5 Modules of space is left, select the object with next largest p_i / w_i ratio, so $x_3 = \frac{1}{2}$ and the profit earned is 7.5.

This solution is the optimal solution

3.3 JOB SEQUENCING WITH DEADLINES

Given a set of 'n' jobs. Associated with each Job i , deadline $d_i > 0$ and profit $P_i > 0$. 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 $d[J[r]] \leq d[J[r+1]]$.

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:

Algorithm:

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 $J \cup \{i\}$ can be completed by their deadlines) then $J := J \cup \{i\};$

}

}

The greedy algorithm is used to obtain an optimal solution.

We must formulate an optimization measure to determine how the next job is chosen.

Algorithm js(d, j, n)

//d dead line, j subset of jobs ,n total number of jobs

// d[i] 1 ≤ i ≤ n are the dead lines,

// the jobs are ordered such that $p[1] \leq p[2] \leq \dots \leq p[n]$

//j[i] is the ith job in the optimal solution 1 ≤ i ≤ k, k subset range

{

d[0]=j[0]=0;

j[1]=1;

k=1;

for i=2 to n do{

r=k;

while((d[j[r]]>d[i]) and (d[j[r]]-r)) do

r=r-1;

if((d[j[r]] ≤ d[i]) and (d[i]-r)) then

{

for q:=k to (r+1) setp-1 do j[q+1]= j[q];

j[r+1]=i;

k=k+1;

}

}


```

return k;

}

```

3.4 The Single Source Shortest-Path Problem

3.4.1 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 - 1do

{

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];

}

}

```

Runningtime:

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
- 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.

Example1:

Use Dijkstra's algorithm to find the shortest path from A to each of the other six vertices in the graph:

The problem is solved by considering the following information:

- Status[v] will be either '0', meaning that the shortest path from v to v0 has definitely been found; or '1', meaning that it hasn't.

- $\text{Dist}[v]$ will be a number, representing the length of the shortest path from v to v_0 found so far.
- $\text{Next}[v]$ will be the first vertex on the way to v_0 along the shortest path found so far from v to v_0

The progress of Dijkstra's algorithm on the graph shown above is as follows:

3.5 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 subsequence.

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.

3.6 MULTI STAGEGRAPHS

A multistage graph $G = (V, E)$ is a directed graph in which the vertices are partitioned into $k > 2$ 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 , $1 \leq i \leq k$. 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 stop path is the result of a sequence of $k-2$ decisions. The i 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:

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

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

ALGORITHM

Algorithm Fgraph(G, k, n, p) // The input is a k -stage graph $G = (V, E)$ with n vertices

// indexed in order of 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

{ // compute cost[j]

let r be a vertex such that (j, r) is an edge of G and $c[j, r] + \text{cost}[r]$ is minimum; cost[j]

:= $c[j, r] + \text{cost}[r]$;

$d[j] := r$;

}

$p[1] := 1$; $p[k] := n$; // 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:

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

$l \in V_{i-1}$

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

Algorithm Bgraph(G, k, n, p)

// Same function as Fgraph

{

$\text{Bcost}[1] := 0.0;$

 for $j := 2$ to n do

 { // Compute $\text{Bcost}[j]$.

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

$D[j] := r;$

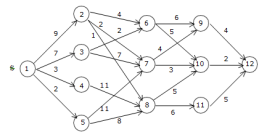
 } // find a minimum costpath $p[1] := 1; p[k] := n;$

 for $j := k-1$ to 2 do $p[j] := D[p[j+1]];$

}

EXAMPLE1:

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.



$\text{linVi} + 1$

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

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

$c(1, 5) + \text{cost}(2, 5)\}$

$= \min \{9 + \text{cost}(2, 2), 7 + \text{cost}(2, 3), 3 + \text{cost}(2, 4), 2 + \text{cost}(2, 5)\}$

Now first starting with,

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$\text{cost}(2, 4) = \min \{c(4, 8) + \text{cost}(3, 8)\} = \min \{11 + 7\} = 18$ $\text{cost}(2, 5) = \min \{c(5, 7) + \text{cost}(3, 7), c(5, 8) + \text{cost}(3, 8)\} = \min \{11 + 5, 8 + 7\} = \min \{16, 15\} = 15$

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

The minimum cost path is 16.

BACKWARD APPROACH: We use the following equation to find the minimum cost path from t to s : $\text{Bcost}(i, J) = \min \{\text{Bcost}(i-1, l) + c(l, J) \mid i-1 < l, j \in E\}$ $\text{Bcost}(5, 12) = \min \{\text{Bcost}(4, 9) + c(9, 12), \text{Bcost}(4, 10) + c(10, 12), \text{Bcost}(4, 11) + c(11, 12)\} = \min \{\text{Bcost}(4, 9) + 4, \text{Bcost}(4, 10) + 2, \text{Bcost}(4, 11) + 5\}$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.7 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 $O(n^2)$ time, the matrix A can be obtained in $O(n^3)$ 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:

$$A_k(i, j) = \min \{ \min \{A_{k-1}(i, k) + A_{k-1}(k, j)\}, c(i, j) \}$$

$1 < k < n$

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 $O(n^3)$.

General formula: $\min \{A_{k-1}(i, k) + A_{k-1}(k, j), c(i, j)\}$

$1 < k < n$

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

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

$A_1(1, 1) = \min \{(A_0(1, 1) + A_0(1, 1)), c(1, 1)\} = \min \{0 + 0, 0\} = 0$

$A_1(1, 2) = \min \{(A_0(1, 1) + A_0(1, 2)), c(1, 2)\} = \min \{(0 + 4), 4\} = 4$

$$A1(1, 3) = \min \{(Ao(1, 1) + Ao(1, 3)), c(1, 3)\} = \min \{(0 + 11), 11\} = 11$$

$$A1(2, 1) = \min \{(Ao(2, 1) + Ao(1, 1)), c(2, 1)\} = \min \{(6 + 0), 6\} = 6$$

$$A1(2, 2) = \min \{(Ao(2, 1) + Ao(1, 2)), c(2, 2)\} = \min \{(6 + 4), 0\} = 0$$

$$A1(2, 3) = \min \{(Ao(2, 1) + Ao(1, 3)), c(2, 3)\} = \min \{(6 + 11), 2\} = 2$$

$$A1(3, 1) = \min \{(Ao(3, 1) + Ao(1, 1)), c(3, 1)\} = \min \{(3 + 0), 3\} = 3$$

$$A1(3, 2) = \min \{(Ao(3, 1) + Ao(1, 2)), c(3, 2)\} = \min \{(3 + 4), 0\} = 7$$

$$A1(3, 3) = \min \{(Ao(3, 1) + Ao(1, 3)), c(3, 3)\} = \min \{(3 + 11), 0\} = 0$$

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

$$A2(1, 1) = \min \{(A1(1, 2) + A1(2, 1)), c(1, 1)\} = \min \{(4 + 6), 0\} = 0$$

$$A2(1, 2) = \min \{(A1(1, 2) + A1(2, 2)), c(1, 2)\} = \min \{(4 + 0), 4\} = 4$$

$$A2(1, 3) = \min \{(A1(1, 2) + A1(2, 3)), c(1, 3)\} = \min \{(4 + 2), 11\} = 6$$

$$A2(2, 1) = \min \{(A(2, 2) + A(2, 1)), c(2, 1)\} = \min \{(0 + 6), 6\} = 6$$

$$A2(2, 2) = \min \{(A(2, 2) + A(2, 2)), c(2, 2)\} = \min \{(0 + 0), 0\} = 0$$

$$A2(2, 3) = \min \{(A(2, 2) + A(2, 3)), c(2, 3)\} = \min \{(0 + 2), 2\} = 2$$

$$A2(3, 1) = \min \{(A(3, 2) + A(2, 1)), c(3, 1)\} = \min \{(7 + 6), 3\} = 3$$

$$A2(3, 2) = \min \{(A(3, 2) + A(2, 2)), c(3, 2)\} = \min \{(7 + 0), 7\} = 7$$

$$A2(3, 3) = \min \{(A(3, 2) + A(2, 3)), c(3, 3)\} = \min \{(7 + 2), 0\} = 0$$

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

$$A3(1, 1) = \min \{(A2(1, 3) + A2(3, 1)), c(1, 1)\} = \min \{(6 + 3), 0\} = 0$$

$$A3(1, 2) = \min \{(A2(1, 3) + A2(3, 2)), c(1, 2)\} = \min \{(6 + 7), 4\} = 4$$

$$A3(1, 3) = \min \{(A2(1, 3) + A2(3, 3)), c(1, 3)\} = \min \{(6 + 0), 6\} = 6$$

$$A3(2, 1) = \min \{(A2(2, 3) + A2(3, 1)), c(2, 1)\} = \min \{(2 + 3), 6\} = 5$$

$$A3(2, 2) = \min \{(A2(2, 3) + A2(3, 2)), c(2, 2)\} = \min \{(2 + 7), 0\} = 0$$

$$A_3(2, 3) = \min \{A_2(2, 3) + A_2(3, 3), c(2, 3)\} = \min \{(2 + 0), 2\} = 2$$

$$A_3(3, 1) = \min \{A_2(3, 3) + A_2(3, 1), c(3, 1)\} = \min \{(0 + 3), 3\} = 3$$

$$A_3(3, 2) = \min \{A_2(3, 3) + A_2(3, 2), c(3, 2)\} = \min \{(0 + 7), 7\} = 7$$

$$A_3(3, 3) = \min \{A_2(3, 3) + A_2(3, 3), c(3, 3)\} = \min \{(0 + 0), 0\} = 0$$

3.8 TRAVELLING SALES PERSON 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 $c_{ij} = 0$ if $(i, j) \notin E$. 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 principle of optimality it follows that:

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

3.8.1 Complexity Analysis

:

For each value of $|S|$ there are $n-1$ choices for i . The number of distinct sets S of

size k not including 1 and i is k . Hence, the total number of $g(i, S)$'s to be computed before computing $g(1, V - \{1\})$

To calculate this sum, we use the binomial theorem: This is $\sum_{k=0}^{n-2} \binom{n-2}{k}$, so there are exponential number of calculate. Calculating one $g(i,$

$S)$ require finding the minimum of at most n quantities. Therefore, the entire algorithm is $\sum_{k=0}^{n-2} \binom{n-2}{k} n$. This is better than enumerating all $n!$ different tours to find the best one.

So, we have traded on exponential growth for a much smaller exponential growth. The most serious drawback of this dynamic programming solution is the space needed, which is $O(n^2)$. This is too large even for modest values of n .

Example1:

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

The cost adjacency matrix =

0	10	15	20	5	0	9	10	6	13	0	12
8	8	9	0								

Let us start the tour from vertex1:

$g(1, V - \{1\}) = \min \{c_{1k} + g(k, V - \{1, k\})\} - (1) \quad 2 \leq k \leq n$ More generally writing:

$g(i, s) = \min \{c_{ij} + g(j, s - \{j\})\} - (2)$ Clearly, $g(i, 0) = c_{i1}, 1 \leq i \leq n$. $g(2, 0) = C_{21} = 5$

$g(3, 0) = C_{31} = 6$ $g(4, 0) = C_{41} = 8$ Using equation - (2) we obtain:

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

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

$g(3, \{4\}) = \min \{c_{34} + g(4, 0)\} = 12 + 8 = 20$

$g(4, \{3\}) = \min \{c_{43} + g(3, 0)\} = 9 + 6 = 15$

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

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

$g(2, \{4\}) = \min \{c_{24} + g(4, 0)\} = 10 + 8 = 18$

$g(4, \{2\}) = \min \{c_{42} + g(2, 0)\} = 8 + 5 = 13$

Therefore, $g(3, \{2, 4\}) = \min \{13 + 18, 12 + 13\} = \min \{31, 25\} = 25$

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

$g(2, \{3\}) = \min \{c_{23} + g(3, 0)\} = 9 + 6 = 15$

$$g(3, \{2\}) = \min \{c_{32} + g(2, 0) = 13 + 5 = 18$$

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

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

The optimal tour for the graph has length = 35 The optimal tour is: 1, 2, 4, 3, 1.

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

The optimal tour for the graph has length = 35 The optimal tour is: 1, 2, 4, 3, 1.

3.9 OPTIMAL BINARY SEARCH TREE

Let us assume that the given set of identifiers is $\{a_1, \dots, a_n\}$ with $a_1 < a_2 < \dots < a_n$. Let $p(i)$ be the probability with which we search for a_i . Let $q(i)$ be the probability that the identifier x being searched for is such that $a_i < x < a_{i+1}$, $0 < i < n$ (assume $a_0 = -$ and $a_{n+1} = +$). We have to arrange the identifiers in a binary search tree in a way that minimizes the expected total access time. In a binary search tree, the number of comparisons needed to access an element at depth ' d ' is $d + 1$, so if ' a_i ' is placed at depth ' d_i ', then we want to minimize:

Let $P(i)$ be the probability with which we shall be searching for ' a_i '. Let $Q(i)$ be the probability of an un-successful search. Every internal node represents a point where a successful search may terminate. Every external node represents a point where an unsuccessful search may terminate.

The expected cost contribution for the internal node for ' a_i ' is: $P(i) * \text{level}(a_i)$.

Unsuccessful search terminate with $I = 0$ (i.e at an external node). Hence the cost contribution for this node is:

$$Q(i) * \text{level}((E_i) - 1)$$

The expected cost of binary search tree is:

Given a fixed set of identifiers, we wish to create a binary search tree organization. We may expect different binary search trees for the same identifier set to have different performance characteristics.

The computation of each of these $c(i, j)$'s requires us to find the minimum of m quantities. Hence, each such $c(i, j)$ can be computed in time $O(m)$. The total time for all $c(i, j)$'s with $j - i = m$ is therefore $O(nm - m^2)$.

Example 1: The possible binary search trees for the identifier set $(a_1, a_2, a_3) = (\text{do}, \text{if}, \text{stop})$ are as follows. Given the equal probabilities $p(i) = Q(i) = 1/7$ for all i , we have:

Huffman coding tree solved by a greedy algorithm has a limitation of having the data only at the leaves and it must not preserve the property that all nodes to the left of the root have keys, which are less etc. Construction of an optimal binary search tree is harder, because the data is not constrained to appear only at the leaves, and also because the tree must satisfy the binary search tree property and it must preserve the property that all nodes to the left of the root have keys, which are less.

A dynamic programming solution to the problem of obtaining an optimal binary search tree can be viewed by constructing a tree as a result of sequence of decisions by holding the principle of optimality. A possible approach to this is to make a decision as which of the a_i 's be assigned to the root node at 'T'. If we choose ' a_k ' then it is clear that the internal nodes for a_1, a_2, \dots, a_{k-1} as well as the external nodes for the classes E_0, E_1, \dots, E_{k-1} will lie in the left sub tree, L, of the root. The remaining nodes will be in the right subtree, R. The structure of an optimal binary search tree is:

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

$$C(i, J) = \min \{C(i, k-1) + C(k, J) + P(K) + w(i, K-1) + w(K, J)\} \quad i < k < J$$

$$= \min \{C(i, K-1) + C(K, J)\} + w(i, J) - (1) \quad i < k < J$$

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

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

Equation (1) may be solved for $C(0, n)$ by first computing all $C(i, J)$ such that $J - i = 1$. Next, we can compute all $C(i, J)$ such that $J - i = 2$, Then all $C(i, J)$ with $J - i = 3$ and soon.

$C(i, J)$ is the cost of the optimal binary search tree 'Tij' during computation we record the root $R(i, J)$ of each tree 'Tij'. 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.

The results are tabulated to recover the actual tree.

Example1:

Let $n = 4$, and $(a_1, a_2, a_3, a_4) = (\text{do}, \text{if}, \text{need}, \text{while})$ Let $P(1: 4) = (3, 3, 1, 1)$ and $Q(0: 4) = (2, 3, 1, 1, 1)$

Solution: Table for recording $W(i, j)$, $C(i, j)$ and $R(i, j)$:

This computation is carried out row-wise from row 0 to row 4. Initially, $W(i, i) = Q(i)$ and $C(i, i) = 0$ and $R(i, i) = 0$, $0 \leq i < 4$.

Solving for $C(0, n)$:

First, computing all $C(i, j)$ such that $j - i = 1$; $j = i + 1$ and as $0 \leq i < 4$; $i = 0, 1, 2$ and 3 ; $i < j$. Start with $i = 0$; so $j = 1$; as $i < k \leq j$, so the possible value for $k = 1$

$W(0, 1) = P(1) + Q(1) + W(0, 0) = 3 + 3 + 2 = 8$ $C(0, 1) = W(0, 1) + \min \{C(0, 0) + C(1, 1)\} = 8$ $R(0, 1) = 1$ (value of 'K' that is minimum in the above equation).

Next with $i = 1$; so $j = 2$; as $i < k \leq j$, so the possible value for $k = 2$ $W(1, 2) = P(2) + Q(2) + W(1, 1) = 3 + 1 + 3 = 7$ $C(1, 2) = W(1, 2) + \min \{C(1, 1) + C(2, 2)\} = 7$ $R(1, 2) = 2$

Next with $i = 2$; so $j = 3$; as $i < k \leq j$, so the possible value for $k = 3$

$W(2, 3) = P(3) + Q(3) + W(2, 2) = 1 + 1 + 1 = 3$ $C(2, 3) = W(2, 3) + \min \{C(2, 2) + C(3, 3)\} = 3 + [(0 + 0)] = 3$ $R(2, 3) = 3$ Next with $i = 3$; so $j = 4$; as $i < k \leq j$, so

the possible value for $k=4$ $W(3, 4) = P(4) + Q(4) + W(3, 3) = 1 + 1 + 1 = 3$ $C(3, 4) = W(3, 4) + \min \{[C(3, 3) + C(4, 4)]\} = 3 + [(0 + 0)] = 3$ $R(3, 4) = 4$

Second, Computing all $C(i, j)$ such that $j - i = 2$; $j = i + 2$ and as $0 < i < 3$; $i = 0, 1, 2$; $i < k - J$. Start with $i = 0$; so $j = 2$; as $i < k - J$, so the possible values for $k = 1$ and 2 .

$W(0, 2) = P(2) + Q(2) + W(0, 1) = 3 + 1 + 8 = 12$ $C(0, 2) = W(0, 2) + \min \{(C(0, 0) + C(1, 2)), (C(0, 1) + C(2, 2))\} = 12 + \min \{(0 + 7, 8 + 0)\} = 19$ $R(0, 2) = 1$

Next, with $i = 1$; so $j = 3$; as $i < k - J$, so the possible value for $k = 2$ and 3 .

$W(1, 3) = P(3) + Q(3) + W(1, 2) = 1 + 1 + 7 = 9$ $C(1, 3) = W(1, 3) + \min \{[C(1, 1) + C(2, 3)], [C(1, 2) + C(3, 3)]\} = 9 + \min \{(0 + 3), (7 + 0)\} = 9 + 3 = 12$ $R(1, 3) = 2$ Next, with $i = 2$; so $j = 4$; as $i < k - J$, so the possible value for $k = 3$ and 4 . $W(2, 4) = P(4) + Q(4) + W(2, 3) = 1 + 1 + 3 = 5$ $C(2, 4) = W(2, 4) + \min \{[C(2, 2) + C(3, 4)], [C(2, 3) + C(4, 4)]\} = 5 + \min \{(0 + 3), (3 + 0)\} = 5 + 3 = 8$ $R(2, 4) = 3$

Third, Computing all $C(i, j)$ such that $J - i = 3$; $j = i + 3$ and as $0 < i < 2$; $i = 0, 1$; $i < k - J$. Start with $i = 0$; so $j = 3$; as $i < k - J$, so the possible values for $k = 1, 2$ and 3 .

$W(0, 3) = P(3) + Q(3) + W(0, 2) = 1 + 1 + 12 = 14$ $C(0, 3) = W(0, 3) + \min \{[C(0, 0) + C(1, 3)], [C(0, 1) + C(2, 3)], [C(0, 2) + C(3, 3)]\} = 14 + \min \{(0 + 12), (8 + 3), (19 + 0)\} = 14 + 11 = 25$ $R(0, 3) = 2$ Start with $i = 1$; so $j = 4$; as $i < k - J$, so the possible values for $k = 2, 3$ and 4 . $W(1, 4) = P(4) + Q(4) + W(1, 3) = 1 + 1 + 9 = 11$ $C(1, 4) = W(1, 4) + \min \{[C(1, 1) + C(2, 4)], [C(1, 2) + C(3, 4)], [C(1, 3) + C(4, 4)]\} = 11 + \min \{(0 + 8), (7 + 3), (12 + 0)\} = 11 + 8 = 19$ $R(1, 4) = 2$

Fourth, Computing all $C(i, j)$ such that $j - i = 4$; $j = i + 4$ and as $0 < i < 1$; $i = 0$; $i < k - J$.

Start with $i = 0$; so $j = 4$; as $i < k - J$, so the possible values for $k = 1, 2, 3$ and 4 .

$W(0, 4) = P(4) + Q(4) + W(0, 3) = 1 + 1 + 14 = 16$ $C(0, 4) = W(0, 4) + \min \{[C(0, 0) + C(1, 4)], [C(0, 1) + C(2, 4)], [C(0, 2) + C(3, 4)], [C(0, 3) + C(4, 4)]\} = 16 + \min [0 + 19, 8 + 8, 19 + 3, 25 + 0] = 16 + 16 = 32$ $R(0, 4) = 2$

From the table we see that $C(0, 4) = 32$ is the minimum cost of a binary search tree for (a_1, a_2, a_3, a_4) . The root of the tree 'T04' is 'a2'.

Hence the left sub tree is 'T01' and right sub tree is T24. The root of 'T01' is 'a1' and the root of 'T24' is a3.

The left and right sub trees for 'T01' are 'T00' and 'T11' respectively. The root of T01 is 'a1'

The left and right sub trees for T24 are T22 and T34 respectively. The root of T24 is 'a3'. The root of T22 is null The root of T34 is a4.

Example2:

Consider four elements a1, a2, a3 and a4 with $Q_0 = 1/8$, $Q_1 = 3/16$, $Q_2 = Q_3 = Q_4 = 1/16$ and $p_1 = 1/4$, $p_2 = 1/8$, $p_3 = p_4 = 1/16$. Construct an optimal binary search tree. Solving for C (0,n):

First, computing all C (i, j) such that $j - i = 1$; $j = i + 1$ and as $0 < i < 4$; $i = 0, 1, 2$ and 3 ; $i < k - j$. Start with $i = 0$; so $j = 1$; as $i < k - j$, so the possible value for $k = 1$

$$W(0, 1) = P(1) + Q(1) + W(0, 0) = 4 + 3 + 2 = 9$$

$$C(0, 1) = W(0, 1) + \min \{C(0, 0) + C(1, 1)\} = 9 + [(0 + 0)] = 9$$

$R(0, 1) = 1$ (value of 'K' that is minimum in the above equation). Next with $i = 1$; so $j = 2$; as $i < k - j$, so the possible value for $k = 2$

$$W(1, 2) = P(2) + Q(2) + W(1, 1) = 2 + 1 + 3 = 6$$

$$C(1, 2) = W(1, 2) + \min \{C(1, 1) + C(2, 2)\} = 6 + [(0 + 0)] = 6$$

$$R(1, 2) = 2$$

Next with $i = 2$; so $j = 3$; as $i < k - j$, so the possible value for $k = 3$ $W(2,$

$$3) = P(3) + Q(3) + W(2, 2) = 1 + 1 + 1 = 3$$

$$C(2, 3) = W(2, 3) + \min \{C(2, 2) + C(3, 3)\} = 3 + [(0 + 0)] = 3$$

$$R(2, 3) = 3$$

Next with $i = 3$; so $j = 4$; as $i < k - j$, so the possible value for $k = 4$ $W(3, 4) = P(4) + Q(4) + W(3, 3) = 1 + 1 + 1 = 3$

$$C(3, 4) = W(3, 4) + \min \{[C(3, 3) + C(4, 4)]\} = 3 + [(0 + 0)] = 3$$

$$R(3, 4) = 4$$

Second, Computing all $C(i, j)$ such that $j - i = 2$; $j = i + 2$ and as $0 < i < 3$; $i = 0, 1, 2$; $i < k - J$

Start with $i = 0$; so $j = 2$; as $i < k - j$, so the possible values for $k = 1$ and 2 . $W(0, 2) = P(2) + Q(2) + W(0, 1) = 2 + 1 + 9 = 12$

$$\begin{aligned} C(0, 2) &= W(0, 2) + \min \{(C(0, 0) + C(1, 2)), (C(0, 1) + C(2, 2))\} \\ &= 12 + \min \{(0 + 6, 9 + 0)\} = 12 + 6 = 18 \end{aligned}$$

$$R(0, 2) = 1$$

Next, with $i = 1$; so $j = 3$; as $i < k - j$, so the possible value for $k = 2$ and 3 .

$$W(1, 3) = P(3) + Q(3) + W(1, 2) = 1 + 1 + 6 = 8$$

$$\begin{aligned} C(1, 3) &= W(1, 3) + \min \{[C(1, 1) + C(2, 3)], [C(1, 2) + C(3, 3)]\} \\ &= W(1, 3) + \min \{(0 + 3), (6 + 0)\} = 8 + 3 = 11 \end{aligned}$$

$$R(1, 3) = 2$$

Next, with $i = 2$; so $j = 4$; as $i < k - j$, so the possible value for $k = 3$ and 4 . $W(2, 4) = P(4) + Q(4) + W(2, 3) = 1 + 1 + 3 = 5$

$$\begin{aligned} C(2, 4) &= W(2, 4) + \min \{[C(2, 2) + C(3, 4)], [C(2, 3) + C(4, 4)]\} \\ &= 5 + \min \{(0 + 3), (3 + 0)\} = 5 + 3 = 8 \end{aligned}$$

$$R(2, 4) = 3$$

Third, Computing all $C(i, j)$ such that $J - i = 3$; $j = i + 3$ and as $0 < i < 2$; $i = 0, 1$;

$i < k - J$. Start with $i = 0$; so $j = 3$; as $i < k - j$, so the possible values for $k = 1, 2$ and 3 .

$$W(0, 3) = P(3) + Q(3) + W(0, 2) = 1 + 1 + 12 = 14$$

$$C(0, 3) = W(0, 3) + \min \{[C(0, 0) + C(1, 3)], [C(0, 1) + C(2, 3)],$$

$$[C(0, 2) + C(3, 3)]$$

$$= 14 + \min \{(0 + 11), (9 + 3), (18 + 0)\} = 14 + 11 = 25$$

$$R(0, 3) = 1$$

Start with $i = 1$; so $j = 4$; as $i < k - j$, so the possible values for $k = 2, 3$ and 4 . $W(1, 4) = P(4) + Q(4) + W(1, 3) = 1 + 1 + 8 = 10$

$$C(1, 4) = W(1, 4) + \min \{[C(1, 1) + C(2, 4)], [C(1, 2) + C(3, 4)],$$

$$[C(1, 3) + C(4, 4)]\}$$

$$= 10 + \min \{(0 + 8), (6 + 3), (11 + 0)\} = 10 + 8 = 18$$

$$R(1, 4) = 2$$

Fourth, Computing all $C(i, j)$ such that $J - i = 4$; $j = i + 4$ and as $0 < i < 1$; $i = 0$;

$i < k - J$. Start with $i = 0$; so $j = 4$; as $i < k - j$, so the possible values for $k = 1, 2, 3$ and 4 .

$$W(0, 4) = P(4) + Q(4) + W(0, 3) = 1 + 1 + 14 = 16$$

$$C(0, 4) = W(0, 4) + \min \{[C(0, 0) + C(1, 4)], [C(0, 1) + C(2, 4)],$$

$$[C(0, 2) + C(3, 4)], [C(0, 3) + C(4, 4)]\}$$

$$= 16 + \min [0 + 18, 9 + 8, 18 + 3, 25 + 0] = 16 + 17 = 33$$

$$R(0, 4) = 2$$

Table for recording $W(i, j)$, $C(i, j)$ and $R(i, j)$

From the table we see that $C(0, 4) = 33$ is the minimum cost of a binary search tree for (a_1, a_2, a_3, a_4)

The root of the tree 'T04' is 'a2'.

Hence the left sub tree is 'T01' and right sub tree is T24. The root of 'T01' is 'a1' and the root of 'T24' is a3.

The left and right sub trees for 'T01' are 'T00' and 'T11' respectively. The root of T01 is 'a1'

The left and right sub trees for T24 are T22 and T34 respectively. The root of T24 is 'a3'. The root of T22 is null. The root of T34 is a4.

0/1 –

3.10 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 is $m - w_n$ 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.

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

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

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

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 , $0 < y < m$. 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 $0 < y < m$. 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 $f_i(y_1) < f_i(y_2) < \dots < f_i(y_k)$; $f_i(y) = -$, $y < y_1$; f_i

$(y) = f_i(y_k)$, $y > y_k$; and $f_i(y) = f_i(y_j)$, $y_j < y < y_{j+1}$. So, we need to compute only $f_i(y_j)$, $1 < j < k$. We use the ordered set $S_i = \{(f_i(y_j), y_j) \mid 1 < j < k\}$ 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:

$$S_{i1} = \{(P, W) \mid (P - p_i, W - w_i) \in S_i\}$$

Now, S_{i+1} can be computed by merging the pairs in S_i and S_{i1} together. Note that if S_{i+1} contains two pairs (P_j, W_j) and (P_k, W_k) with the property that $P_j < P_k$ and $W_j > W_k$, 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 $f_i(x) = -$ if $x < 0$. $F_n(M) = \max \{f_{n-1}(M), f_{n-1}(M - w_n) + p_n\}$

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

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

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

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

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

$$F_2(2) = \max \{f_1(2), f_1(2 - 3) + 2\} = \max \{f_1(2), -0 + 2\}$$

$$F1(2) = \max \{f0(2), f0(2-2) + 1\} = \max \{0, 0 + 1\} = 1$$

$$F2(2) = \max \{1, -0 + 2\} = 1$$

$$\text{Finally, } f3(6) = \max \{3, 1 + 5\} = 6$$

OtherSolution:

For the given data we have:

$$S0 = \{(0,0)\}; S0 = \{(1,2)\} \quad S1 = (S0 \cup S01) = \{(0, 0), (1,2)\}$$

$$X - 2 = 0 \Rightarrow x = 2. \quad y - 3 = 0 \Rightarrow y = 3$$

$$X - 2 = 1 \Rightarrow x = 3. \quad y - 3 = 2 \Rightarrow y = 5$$

$$I = \{(2, 3), (3,5)\}$$

$$S2 = (S1 \cup S1) = \{(0, 0), (1, 2), (2, 3), (3,5)\}$$

$$X - 5 = 0 \Rightarrow x = 5. \quad y - 4 = 0 \Rightarrow y = 4$$

$$X - 5 = 1 \Rightarrow x = 6. \quad y - 4 = 2 \Rightarrow y = 6$$

$$X - 5 = 2 \Rightarrow x = 7. \quad y - 4 = 3 \Rightarrow y = 7$$

$$X - 5 = 3 \Rightarrow x = 8. \quad y - 4 = 5 \Rightarrow y = 9$$

$$I = \{(5, 4), (6, 6), (7, 7), (8,9)\}$$

$$S3 = (S2 \cup S21) = \{(0, 0), (1, 2), (2, 3), (3, 5), (5, 4), (6, 6), (7, 7), (8,9)\}$$

By applying Dominance rule,

$$S3 = (S2 \cup S21) = \{(0, 0), (1, 2), (2, 3), (5, 4), (6,6)\}$$

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

3.11 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 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 $r_i = 0.99$, $i < i < 10$, then $r_i = .904$. Hence, it is desirable to duplicate devices. Multiply copies of the same device type are connected in parallel.

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 $r_i(m_i)$.

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 Module of device i and let C be the maximum allowable cost of the system being designed.

Clearly, $f_0(x) = 1$ for all x , $0 < x < C$ and $f(x) = 0$ for all $x < 0$. Let S_i consist of tuples of the form (f, x) , where $f = f_i(x)$. There is at most one tuple for each different ' x ', that result from a sequence of decisions on m_1, m_2, \dots, m_n . The dominance rule (f_1, x_1) dominates (f_2, x_2) if $f_1 \geq f_2$ and $x_1 > x_2$. Hence, dominated tuples can be discarded from S_i .

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 $x_1 > x_2$, 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 $f_1 \geq f_2$ and $x_1 > x_2$ then discard (f_2, x_2) Case 2: if $f_1 > f_2$ and $x_1 < x_2$ then discard (f_2, x_2) Case 3: otherwise simply write (f_1, x_1)

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

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 $m_1 = 1$.

OtherSolution:

According to the principle of optimality:

$$f_n(C) = \max \{ f_{n-1}(C - c_n) \mid f_{n-1}(x) = 1 \text{ and } 0 \leq x \leq C - c_n \}$$

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

Chapter 4

BACKTRACKING AND BRANCH AND BOUND

Course Outcomes

After successful completion of this module, students should be able to:

CO 6	Find running time and space complexity of given algorithms using techniques such as recurrences, potential functions, properties of probability.	Understand
CO 7	Apply divide and conquer algorithms for solving sorting, searching and matrix multiplication problems..	Apply

4.1 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 requires

a set of constraints divided into two categories: explicit and implicit constraints. 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 . 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 where by, 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. 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. 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 instance. 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. 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.

4.2 N-Queens Problem

Let us consider, $N = 8$. Then 8-Queens Problem is to place eight queens on an 8×8 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 th row where the i 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 -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.

- Diagonal conflict: Two queens i and j are on the same diagonal

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

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

- Diagonal 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 th queen and l be the column of object in row ' k ' for the k th queen.

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

Let us consider for the case whether the queens on 3rd row and 8th row are conflicting or not. In this case $(i, j) = (3, 1)$ and $(k, l) = (8, 6)$ Therefore:

$|j - l| = |i - k|$ is $|1 - 6| = |3 - 8|$ which is $5 = 5$ 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.

Step1: Add to the sequence the next number in the sequence 1, 2, . . . , 8 not yet used.

Step2: 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 Step1.

Step3: 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.

On a chessboard, the solution

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4.3 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.

4.3.1 Sum of Subsets

Given positive numbers $w_i, 1 \leq i \leq n$, and m , this problem requires finding all subsets of w_i 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 a 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 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 soon.

4.4 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, . . . 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
```

```
{ // Generate all legal assignments for x[k].
```

```
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 ndo
{ // 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.

4.5 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 , $1 < i < n$, 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 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 been
// assigned to x [k]. After execution, x[k] is assigned to the next highest numbered vertex
// 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); //Nextvertex.
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 node1.
    {
    repeat
    { // Generate values for x[k].
    NextValue(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);
    }

```

4.6 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 ways:

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.

4.7 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 obtained by using an “intelligent” ranking function

$C(.)$

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 $f(.)$ is any non-decreasing function.

is $g(x)$ 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 next

E-node would always choose for its next E-node a live node with least $c(.)$ is known as LC-search (Least Cost search)

BFS and D-search are special cases of LC-search. If

g

$= 0$ 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 essentially a D-search.

$g(x) >$

$g(y)$ whenever y is a child of x , then this search is

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 an estimate

$c(x)$ of $c(x)$.

Control Abstraction for LC-Search:

Let t be a state space tree and $c()$ 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

$c(\cdot)$ is used to estimate $c()$. 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

$c(x) =$

$c(x)$.

LC-search uses c to find an answer node. The algorithm uses two functions $\text{Least}()$ and $\text{Add}()$ to delete and add a live node from or to the list of live nodes, respectively.

$\text{Least}()$ finds a live node with least $c()$. This node is deleted from the list of live nodes and n returned.

$\text{Add}(x)$ 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 $\text{LCSearch}(t)$

{ //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 livenode.

    (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.

4.7.1 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.

good bounding helps to prune efficiently the tree, leading to a faster exploration of the solutionspace.

A costfunction $c(.)$ such that $c(x) < c(x)$ is used to provide lower bounds on

solutions obtainable from any node x . If $upper$ is an upper bound on the cost of a

minimum-cost solution, then all live nodes x with $c(x) > upper$. The starting

value for $upper$ can be obtained by some heuristic or can be set .

As long as the initial value for $upper$ 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 $upper$ 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 $c(.)$, 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 $c(.)$.

- For nodes representing feasible solutions, $c(x)$ is the value of the objective function for that feasible solution.
- For nodes representing infeasible solutions, $c(x) = 0$.

- 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 (x) such that $(x) < c(x)$ for all x .

Sum-of-Subsets problem

In this problem, we are given a vector of N values, called weights. The weights are usually given in ascending order of magnitude and are unique.

For example, $W = (2, 4, 6, 8, 10)$ is a weight vector. We are also given a value M , for example 20.

The problem is to find all combinations of the weights that exactly add to M .

In this example, the weights that add to 20 are:

$(2, 4, 6, 8)$; $(2, 8, 10)$; and $(4, 6, 10)$.

Solutions to this problem are often expressed by an N -bit binary solution vector, X , where a 1 in position i indicates that W_i is part of the solution and a 0 indicates it is not.

In this manner the three solutions above could be expressed as: $(1,1,1,1,0)$; $(1,0,0,1,1)$; $(0,1,1,0,1)$

Sum-of-Subsets problem

We are given 'n' positive numbers called weights and we have to find all combinations of these numbers whose sum is M . this is called sum of subsets problem.

If we consider backtracking procedure using fixed tuple strategy, the elements $X(i)$ of the solution vector is either 1 or 0 depending on if the weight $W(i)$ is included or not.

If the state space tree of the solution, for a node at level I , the left child corresponds to $X(i)=1$ and right to $X(i)=0$.

Sum of Subsets Algorithm

```
voidSumOfSub(float s, int k, float r)
```

```

{
// Generate left child.

x[k] = 1;

if (s+w[k] == m)

{ for (int j=1; j<=k; j++)

Print (x[j] )

}

else if (s+w[k]+w[k+1] <= m)

SumOfSub(s+w[k], k+1, r-w[k]);

// Generate right child and evaluate

if ((s+r-w[k] >= m) && (s+w[k+1] <= m)) { x[k] = 0;

SumOfSub(s, k+1, r-w[k]);

}

}

```

Sum of Subsets State Space Tree

Example $n=6$, $w[1:6]=\{5,10,12,13,15,18\}$, $m=30$

4.7.2 Branch and Bound Principle

The term branch-and-bound refers to all state space search methods in which all children of the £-node are generated before any other live node can become the £-node. We have already seen two graph search strategies, BFS and D-search, in which the exploration of a new node cannot begin until the node currently being explored is fully explored. Both of these generalize to branch-and-bound strategies.

In branch-and-bound terminology, a BFS-like state space search will be called FIFO (First In First Out) search as the list of live nodes is a first-in-first-out list (or queue). A D-search like state space search will be called LIFO (Last In First Out) search as the list of live nodes is a last-in-first-out list (or stack).

4.8 LC Method Control Abstraction Explanation

The search for an answer node can often be speeded by using an "intelligent" ranking function, $c(\cdot)$, for livenodes. The next \mathcal{L} -node is selected on the basis of this ranking-function. 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. The algorithm uses two subalgorithms $LEAST(X)$ and $ADD(X)$ to respectively delete and add a live node from or to the list of livenodes. $LEAST\{X\}$ finds a live node with least $c(\cdot)$. This node is deleted from the list of live nodes and returned in variable X . $ADD(X)$ adds the new live node X to the list of livenodes. Procedure LC outputs the path from the answer

How to find the upper bound?

Ans: by quickly finding a feasible solution in a greedy manner: starting from the smallest available i , scanning towards the largest i 's until M is exceeded. The upper bound can be calculated.

How to expand the tree?

By the best-first search scheme. That is, by expanding the node with the best lower bound. If two nodes have the same lower bounds, expand the node with the lower upper bound.

0/1 Knapsack Example using LCBB (Least Cost)

Example (LCBB) Consider the knapsack instance: $n = 4$; $(p_1, p_2, p_3, p_4) = (10, 10, 12, 18)$; $(w_1, w_2, w_3, w_4) = (2, 4, 6, 9)$ and $M = 15$.

4.9 The traveling salesperson problem

Given a graph, the TSP Optimization problem is to find a tour, starting from any vertex, visiting every other vertex and returning to the starting vertex, with minimal cost.

The basic idea

There is a way to split the solution space (branch)

There is a way to predict a lower bound for a class of solutions. There is also a way to find an upper bound of an optimal solution. If the lower bound of a solution exceeds the upper bound, this solution cannot be optimal and thus we should terminate the branching associated with this solution.

Example- TSP

Example with Cost Matrix (a) and its Reduced Cost Matrix (b)

Reduced matrix means every row and column of matrix should contain at least one Zero and all other entries should be non negative.

Chapter 5

NP-HARD AND NP-COMPLETE PROBLEM

Course Outcomes

After successful completion of this module, students should be able to:

CO 6	Illustrate the functionality of various types of interrupts and their structure for controlling the processor or controller and program execution flow using Programmable interrupt controller.	Understand
CO 9	Choose an appropriate data transfer scheme and hardware to perform serial data transfer among the devices.	Apply

5.1 Basic concepts

NP Nondeterministic Polynomial time. The problems has best algorithms for their solutions have “Computing times”, that cluster into two groups.

Group-1

Problems with solution time bound by a polynomial of a small degree. They are also called “Tractable Algorithms”. Most Searching & Sorting algorithms are polynomial time algorithms. Ex: Ordered Search ($O(\log n)$), Polynomial evaluation $O(n)$

Sorting $O(n \log n)$

Group-II

Problems with solution times not bound by polynomial (simply non polynomial). These are hard or intractable problems. None of the problems in this group has been solved by any polynomial time algorithm. Ex: Traveling Sales Person $O(2^n)$, Knapsack $O(2^n/2)$

No one has been able to develop a polynomial time algorithm for any problem in the group –II. So, it is compulsory and finding algorithms whose computing times are greater than polynomial very quickly because such vast amounts of time to execute that even moderate size problems cannot be solved.

5.2 Theory of NP-Completeness

Show that many of the problems with no polynomial time algorithms are computational time algorithms are computationally related.

There are two classes of non-polynomial time problems

1. NP-Hard
2. NP-Complete

NP Complete Problem: A problem that is NP-Complete can be solved in polynomial time if and only if (iff) all other NP-Complete problems can also be solved in polynomial time.

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.

5.3 Nondeterministic Algorithms

Algorithms with the property that the result of every operation is uniquely defined are termed as deterministic algorithms. Such algorithms agree with the way programs are executed on a computer.

Algorithms which contain operations whose outcomes are not uniquely defined but are limited to specified set of possibilities. Such algorithms are called nondeterministic algorithms.

The machine executing such operations is allowed to choose any one of these outcomes subject to a termination condition to be defined later.

To specify nondeterministic algorithms, there are 3 new functions.

Choice(S) arbitrarily chooses one of the elements of sets S

Failure () Signals an Unsuccessful completion

Success () Signals a successful completion.

Example for Non Deterministic algorithms:

Algorithm Search(x){

//Problem is to search an element x

//output J, such that $A[J]=x$; or $J=0$ if x is not in A

$J:=\text{Choice}(1,n);$

if($A[J]=x$) then

{

Write(J);

Success();

}

```

else{

write(0);

failure();

}

```

Whenever there is a set of choices that leads to a successful completion then one such set of choices is always made and the algorithm terminates.

A Nondeterministic algorithm terminates unsuccessfully if and only if (iff) there exists no set of choices leading to a successful signal.

5.3.1 Nondeterministic Knapsack algorithm

Algorithm DKP(p, w, n, m, r, x)

```

{

W:=0;

P:=0;

for i:=1 to n do{

x[i]:=choice(0, 1);

W:=W + x[i]*w[i];

P:=P + x[i]*p[i];

}

if( (W>m) or (P<r) ) then Failure();

else Success();

}

p given Profits w given Weights

```


n Number of elements (number of p or w) m Weight of bag limit

P Final Profit W Final weight

5.4 The Classes NP-Hard & NP-Complete

:

For measuring the complexity of an algorithm, we use the input length as the parameter. For example, An algorithm A is of polynomial complexity $p()$ such that the computing time of A is $O(p(n))$ for every input of size n.

Decision problem/ Decision algorithm: Any problem for which the answer is either zero or one is decision problem. Any algorithm for a decision problem is termed a decision algorithm.

Optimization problem/ Optimization algorithm: Any problem that involves the identification of an optimal (either minimum or maximum) value of a given cost function is known as an optimization problem. An optimization algorithm is used to solve an optimization problem.

P is the set of all decision problems solvable by deterministic algorithms in polynomial time.

NP is the set of all decision problems solvable by nondeterministic algorithms in polynomial time.

Since deterministic algorithms are just a special case of nondeterministic, by this we concluded that $P \subseteq NP$

The most famous unsolvable problems in Computer Science is Whether $P=NP$ or $P \neq NP$

In considering this problem, s.cook formulated the following question. If there any single problem in NP, such that if we showed it to be in 'P' then that would imply that $P=NP$.

Cook answered this question with

Theorem: Satisfiability is in P if and only if (iff) $P=NP$

5.5 Notation of Reducibility

Let L_1 and L_2 be problems, Problem L_1 reduces to L_2 (written $L_1 \leq L_2$) 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. This implies that, if we have a polynomial time algorithm for L_2 , Then we can solve L_1 in polynomial time.

Here \leq is a transitive relation i.e., $L_1 \leq L_2$ and $L_2 \leq L_3$ then $L_1 \leq L_3$. A problem L is NP-Hard if and only if (iff) satisfiability reduces to L i.e., $\text{Satisfiability} \leq L$.

A problem L is NP-Complete if and only if (iff) L is NP-Hard and $L \in \text{NP}$.

Commonly believed relationship among P , NP , NP-Complete and NP-Hard

Most natural problems in NP are either in P or NP-complete.

Examples of NP-complete problems:

Packing problems: SET-PACKING, INDEPENDENT-SET.

Covering problems: SET-COVER, VERTEX-COVER.

Sequencing problems: HAMILTONIAN-CYCLE, TSP.

Partitioning problems: 3-COLOR, CLIQUE.

Constraint satisfaction problems: SAT, 3-SAT.

Numerical problems: SUBSET-SUM, PARTITION, KNAPSACK

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