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UNIT-5

Branch and Bound

General Method:- This branch and bound method is used for solving optimization problem and it is similar to Back tracking method. Because it is also uses state space tree. & it is used for solving only minimization problems.

→ The term branch & bound refers to all state space tree search methods in a graph. They are

1) Breadth first search (FIFO)
2) Depth first search (LIFO)
3) Least cost search (LC)

eg:- Jobs { J_1 J_2 J_3 J_4 }

$P = \{10, 5, 8, 3\}$

$d = \{1, 2, 1, 2\}$

$S = \{J_1, J_4\}$ → It is a variable size solution

$S = \{1, 0, 0, 1\}$ → It is a fixed type solution.

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1) First - in first out :-

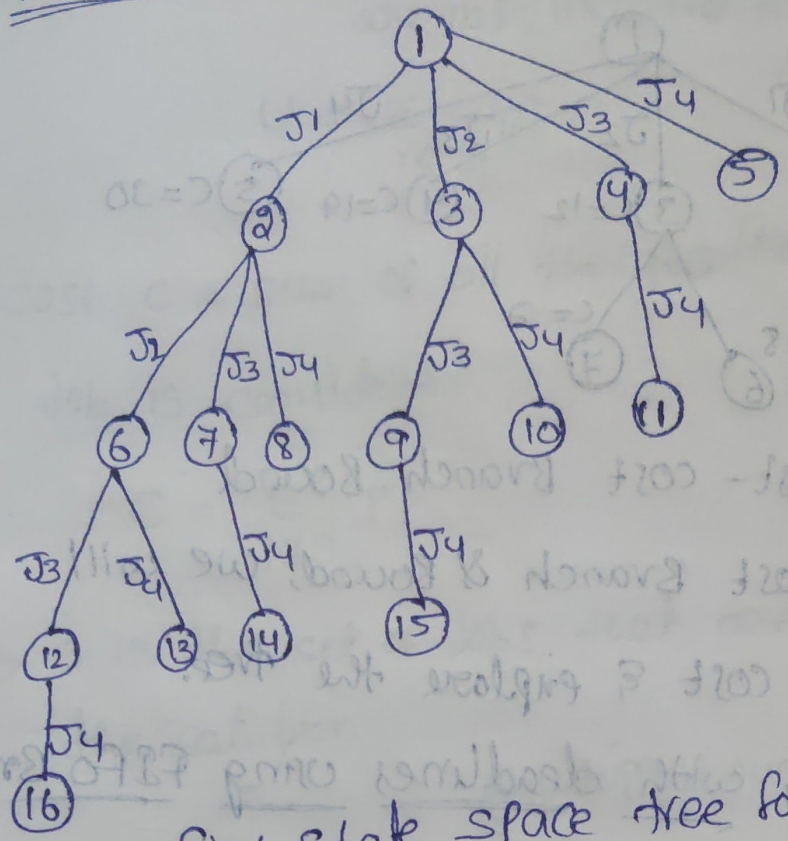

fig: state space tree for FIFO.

2) Last - in first out :-

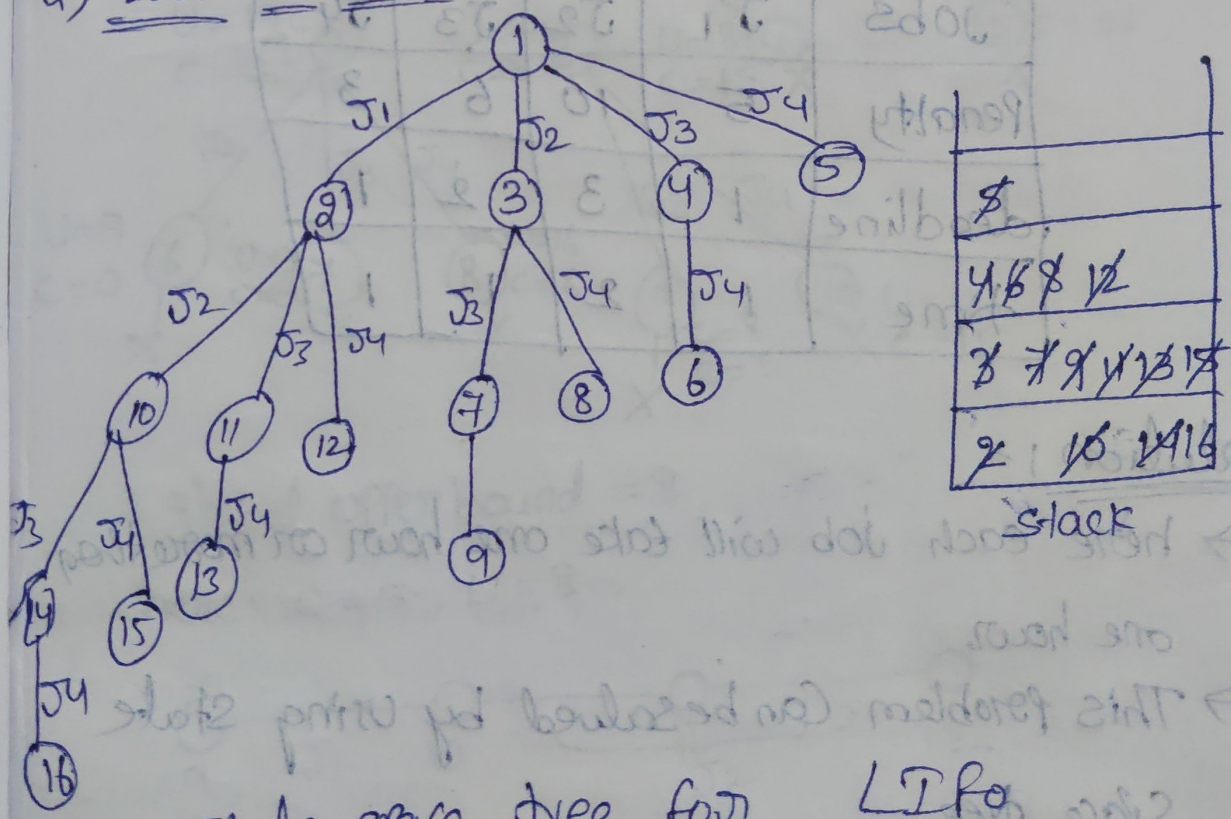

fig: State space tree for LIFO

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3) Least cost search :-

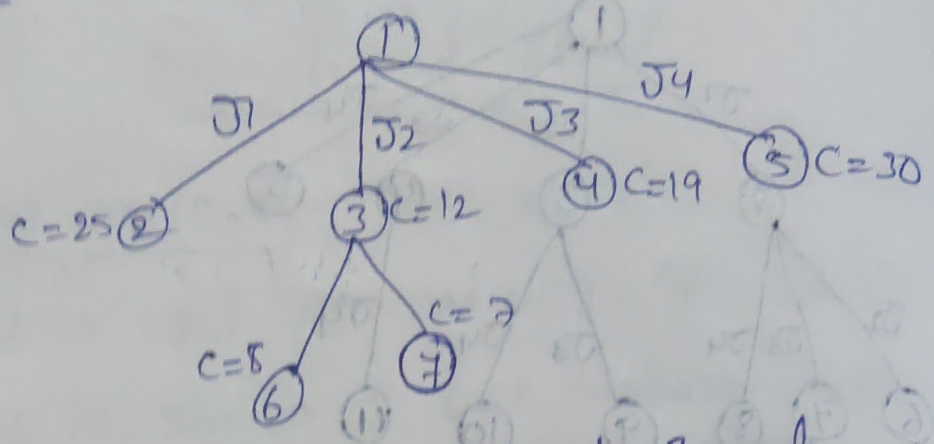

fig: Least-cost Branch Bound.

→ In Least-cost Branch & Bound, we will select least cost & explore the tree.

Job sequencing with deadlines using FIFO Branch & Bound :-

jobs	J1	J2	J3	J4
Penalty	5	10	6	3
deadline	1	3	2	1
time	1	2	1	1

Solution :-

→ here each job will take one hour or more than one hour.

→ This problem can be solved by using state space tree.

→ each node will define 2 values i.e cost & upper bound

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Upper bound U = sum of all the penalties those which are not included in the solution

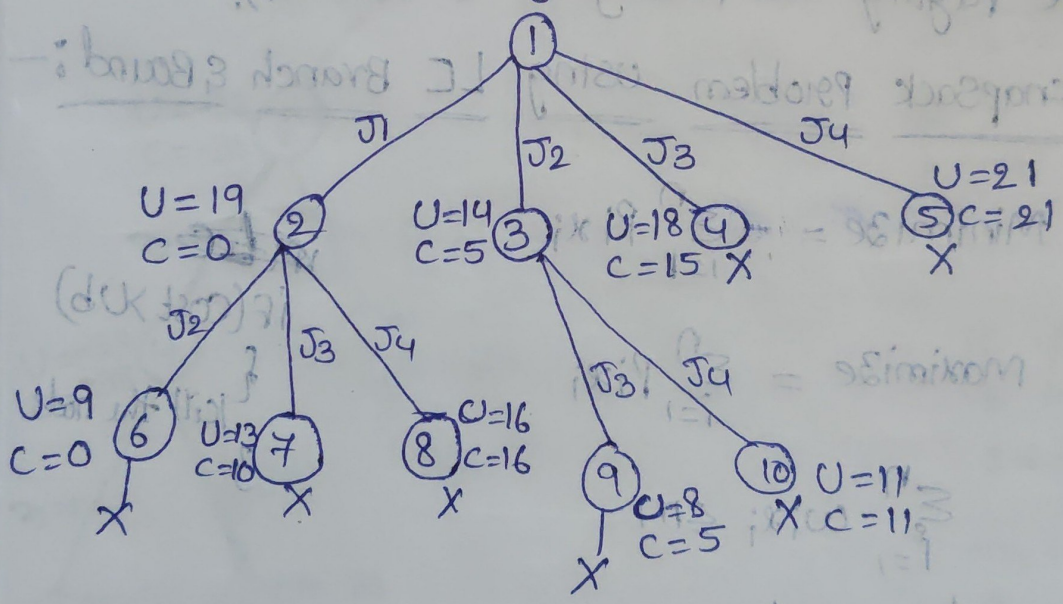
$$U = \sum_{i \notin S} P_i$$

cost C = sum of all the penalties till the last job is considered.

$$C = \sum_{i \notin S_k} P_i$$

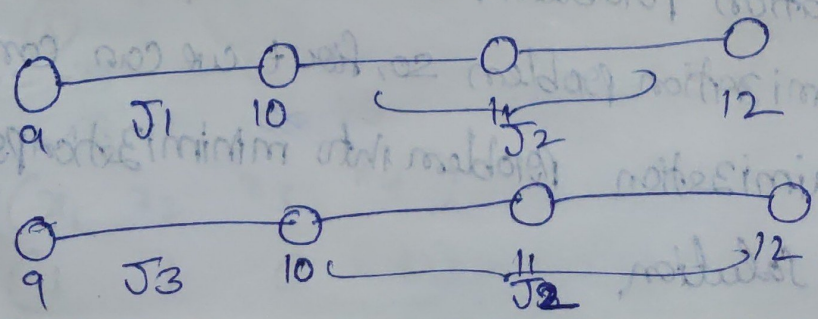
→ S is the set of jobs that are included in the solution

global upper bound = U = ∞ ~~24~~ ~~19~~ ~~14~~ ~~9~~ ~~8~~



global upper bound = 8

here C = 5, U = 8



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J_2 J_3
10 6 = 16 Penalty

J_1 J_4
5 3 = 8 Penalty.

condition:- if (gub > ub)
{
update gub with ub
}
else
{
kill the node.
}

→ here we are doing Job 2 & Job 3, then we are paying the penalty is 8 (J_1, J_4).

0/1 Knapsack Problem using LC Branch & Bound:-

$$\text{Minimize} = -\sum_{i=1}^{n} P_i x_i$$

$$\text{Maximize} = \sum_{i=1}^{n} P_i x_i$$

$$\sum_{i=1}^{n} w_i x_i \le m$$

$x_i = 0/1 \quad 1 \le i \le n$

~~if LC~~
if (cost > ub)
{
kill the node
}

→ The branch and bound method is used for solving minimization problem. but the knapsack problem is maximization problem so, first we can convert the maximization problem into minimization problem & find the solution.

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eg:-

Profit	10	10	12	18
weight	2	4	6	9

$M = 15$

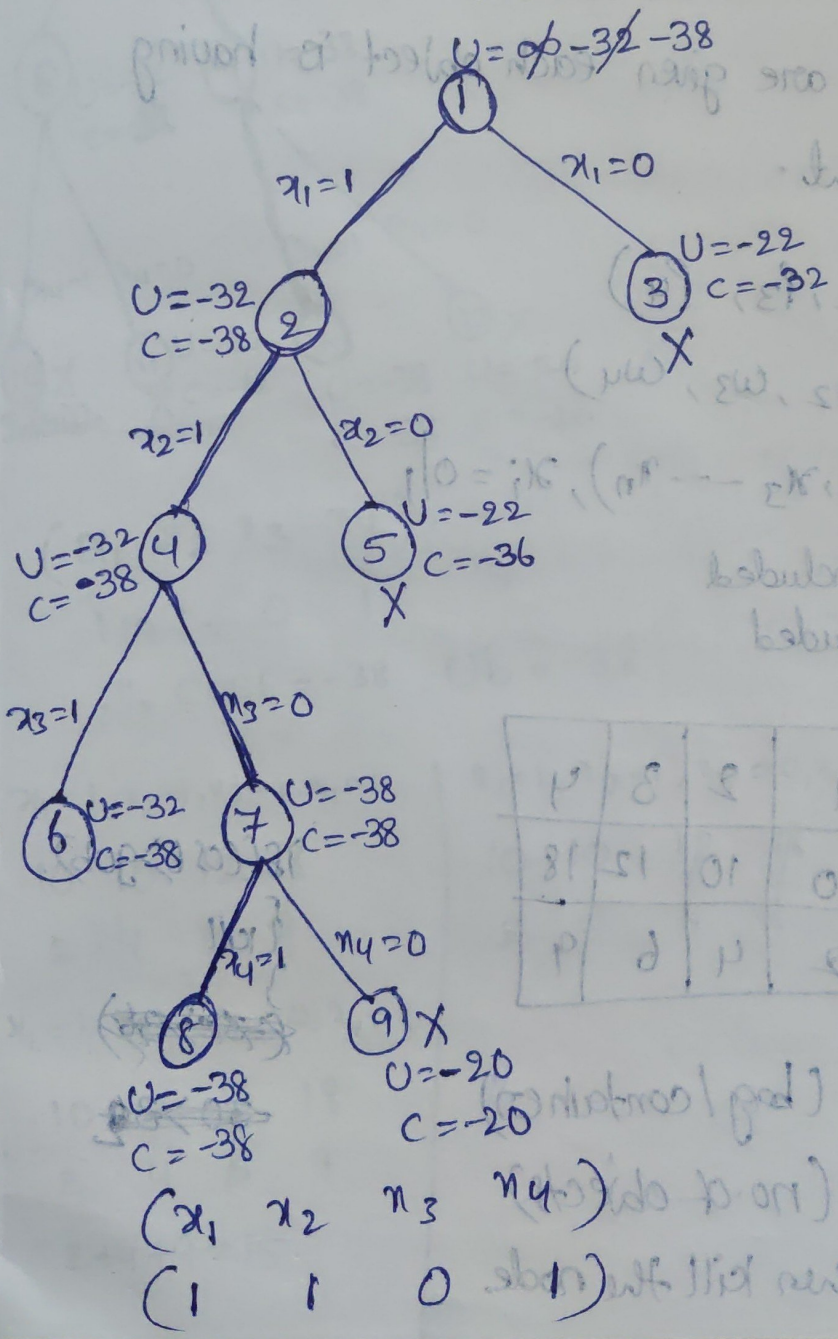
$n = 4$

Let container capacity $M = 15$

no. of objects $N = 4$

upper bound $U = \sum_{i=1}^{n} p_i x_i \le M$ (without fraction)

cost $C = \sum_{i=1}^{n} p_i x_i$ (with fraction)



$(x_1 \quad x_2 \quad x_3 \quad x_4)$

$(1 \quad 1 \quad 0 \quad 1)$

10 10 12 ~~18~~ 2 ×3

2 4 6 9

15 - 12 = 3

~~10~~ 10 12 ~~18~~ 2 ×5

~~2~~ 4 6 ~~9~~

4+6 = 10-15 = 5

10 ~~10~~ 12 ~~18~~ 2 ×7

2 4 6 ~~9~~

2+6 = 8-15 = 7

10 10 ~~12~~ 18

2 4 ~~6~~ 9

2+4+9 = 15

10 10 ~~12~~ 18

2 4 ~~6~~ 9

10 10 ~~12~~ ~~18~~

2 4 ~~6~~ ~~9~~

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$10+10+0+18 = 38$ Maximum profit

$2+4+0+9 = 15$ Cost

$$\sum_{i=1}^{n} w_i x_i \leq M$$

$$\boxed{15 \leq 15}$$

0/1 knapsack problem using FIFO Branch & Bound:

FIFO → First in First out

Let n objects are given each object is having profit & weight.

(P_1, P_2, P_3, P_4)

(w_1, w_2, w_3, w_4)

$x_i = (x_1, x_2, x_3 \ldots x_n), x_i = 0/1$

$x_i = 0$ → not included

1 → included

objects	1	2	3	4
profit	10	10	12	18
weight	2	4	6	9

if(cost > gub)

{ kill

}

~~(cost > gub)~~

~~30 > 38~~

$M = 15$ (bag / container)

$N = 4$ (no. of objects)

→ cost > gub then kill the node.

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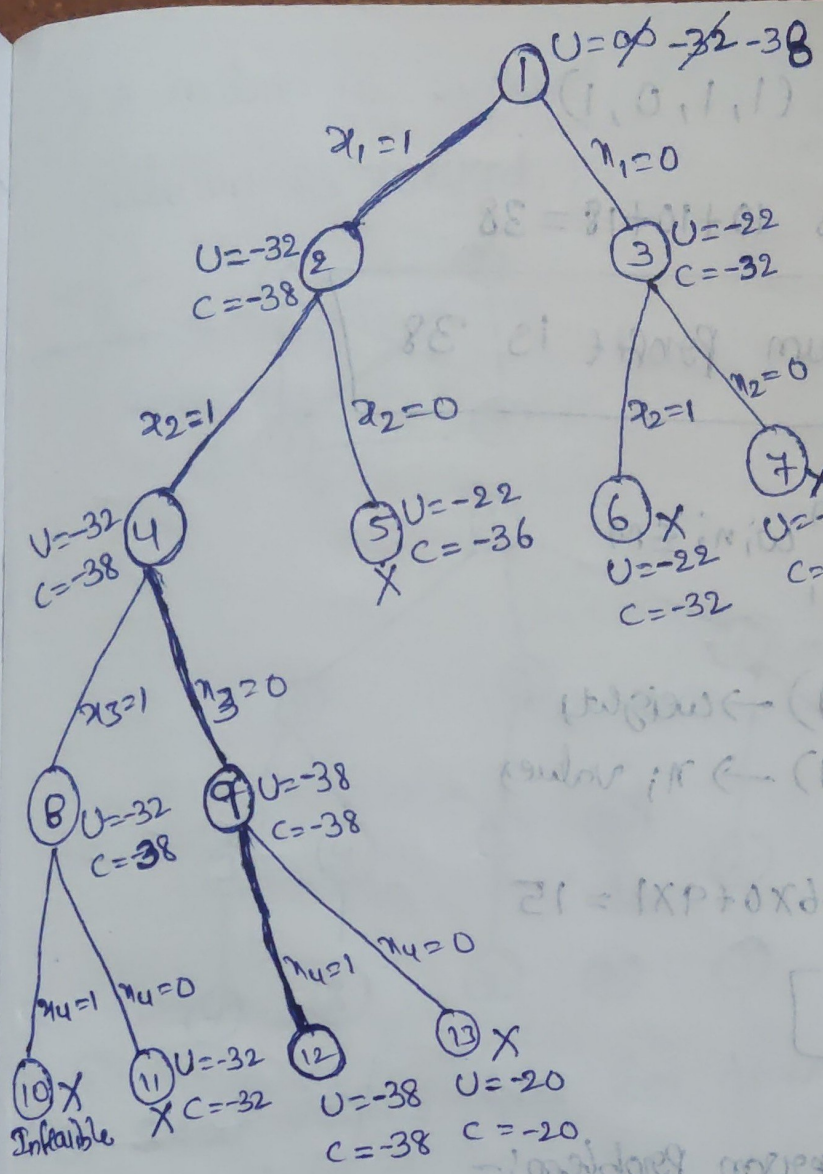

$x_1 = 1$

10 10 12 ~~18~~ 2 ×3

2 + 4 + 6 ~~9~~

15 − 12 = 3

$x_1 = 0$

~~10~~ 10 12 ~~18~~ 2 ×5

~~2~~ 4 6 ~~9~~

4 + 6 = 10 − 15 = 5

$x_2 = 1$

10 10 12 ~~18~~ 2 ×3

2 4 6 ~~9~~

2 + 4 + 6 = 12 − 15 = 3

$x_2 = 0$

10 ~~10~~ 12 ~~18~~ 2 ×7

2 ~~4~~ 6 ~~9~~

2 + 6 = 8 − 15 = 7

$x_1 = 0, x_2 = 1$

~~10~~ 10 12 18

~~2~~ 4 6 9

$x_1 = 0, x_2 = 0$

~~10~~ ~~10~~ 12 18

~~2~~ ~~4~~ 6 9

6 + 9 = 15

$(x_1\ x_2\ x_3\ x_4)$

1 1 0 1

∴ cost = −38, Ub = −38

$x_1 = 1, x_2 = 1, x_3 = 1\ x_4 = 1$

10 10 12 ~~18~~

2 4 6 ~~9~~

$x_1 = 1, x_2 = 1, x_3 = 0, x_4 = 1$

10 10 ~~12~~ 18

2 4 ~~6~~ 9

2 + 4 + 9 = 15

$x_1 = 1, x_2 = 1, x_3 = 0, x_4 = 0$

10 10 ~~12~~ ~~18~~

2 4 ~~6~~ ~~9~~

$x_1 = 1, x_2 = 1, x_3 = 0$

10 10 ~~12~~ 18

2 4 ~~6~~ 9

2 + 4 + 9 = 15

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solution = (1, 1, 0, 1)

Profit is 10+10+18 = 38

Maximum profit is 38

Weight = $\sum_{i=1}^{n} w_i x_i \leq M$

= (2, 4, 6, 9) → weights

(1, 1, 0, 1) → x_i values

= 2×1 + 4×1 + 6×0 + 9×1 = 15

$\boxed{15 \leq 15}$

Traveling salesperson problem:-

Let G = (V, E) be a directed graph defining an instance of the traveling salesperson problem.

→ we can assume that every tour starts and ends at vertex 1.

→ A better $\hat{c}(\cdot)$ can be obtained by using the reduced cost matrix corresponding to G.

→ A row is said to be reduced iff it contains at least one zero & all remaining entries are non-negative.

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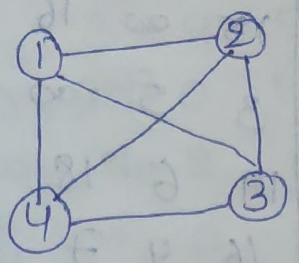
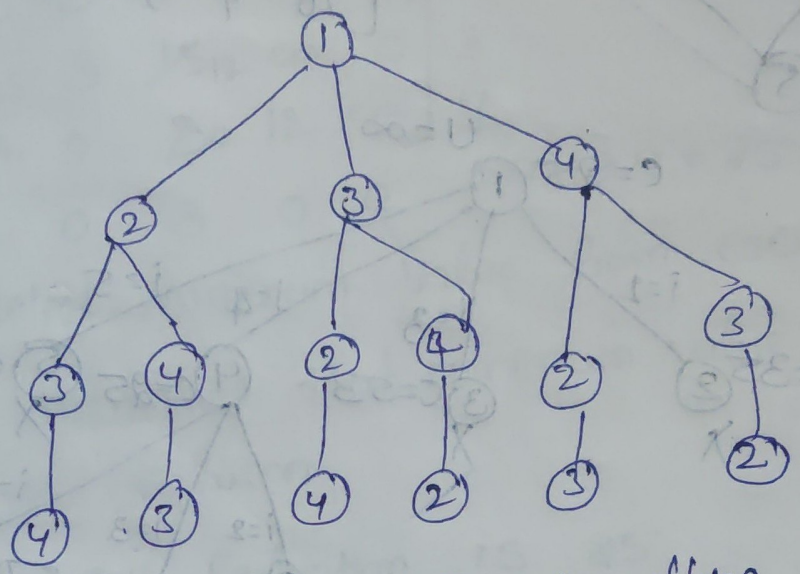
→ A matrix is reduced iff every row and column is reduced.

eg:-





fig; state space tree for travelling salesperson problem

eg:- A weighted graph is given with 5 vertices and we have to find out shortest tour that is going to all the vertices once and returning back to the starting vertex.

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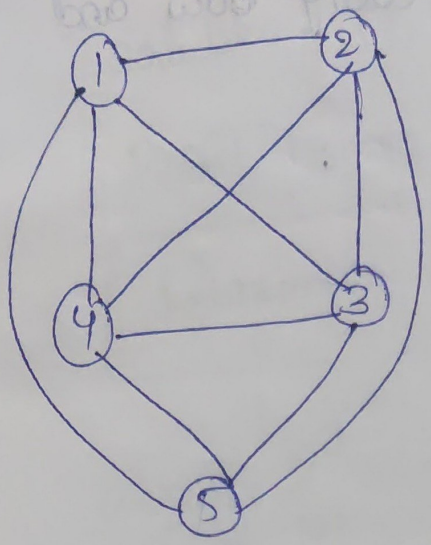
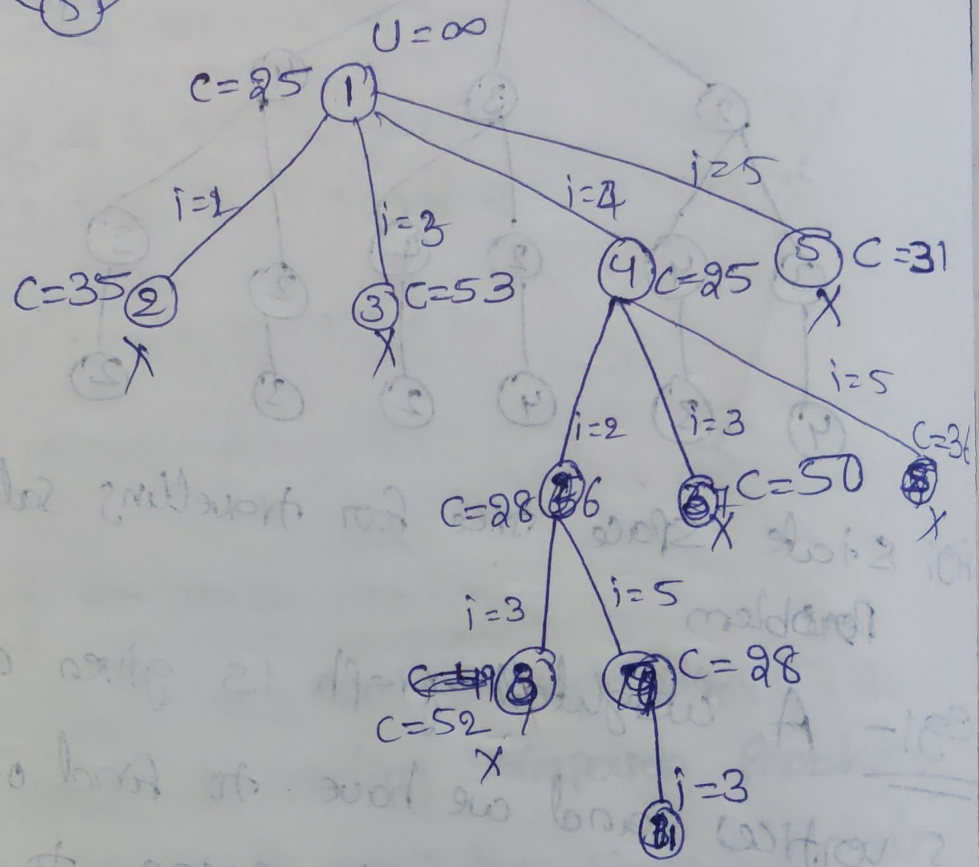


$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & 20 & 30 & 10 & 11 \\ 2 & 15 & \infty & 16 & 4 & 2 \\ 3 & 3 & 5 & \infty & 2 & 4 \\ 4 & 19 & 6 & 18 & \infty & 3 \\ 5 & 16 & 4 & 7 & 16 & \infty \end{array}$$



$$\begin{array}{c|ccccc|c} & 1 & 2 & 3 & 4 & 5 & \\ \hline 1 & \infty & 20 & 30 & 10 & 11 & 10 \\ 2 & 15 & \infty & 16 & 4 & 2 & 2 \\ 3 & 3 & 5 & \infty & 2 & 4 & 2 \\ 4 & 19 & 6 & 18 & \infty & 3 & 3 \\ 5 & 16 & 4 & 7 & 16 & \infty & 4 \end{array}$$

→ Select minimum value from each row

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→ Now, subtract that minimum values from all the rows.

$$
\begin{array}{c|ccccc|c}
 & 1 & 2 & 3 & 4 & 5 & \\
\hline
1 & \infty & 10 & \cancel{20}\,7 & 0 & 1 & 10 \\
2 & \cancel{13}\,12 & \infty & \cancel{14}\,11 & 2 & 0 & 2 \\
3 & \cancel{0}\,0 & 3 & \infty & 0 & 2 & 2 \\
4 & \cancel{16}\,15 & 3 & \cancel{15}\,12 & \infty & 0 & 3 \\
5 & \cancel{12}\,11 & 0 & \cancel{B}\,0 & 12 & \infty & 4 \\
\hline
 & 1 & 0 & 3 & 0 & 0 &
\end{array}
$$

$\Rightarrow 21 + 4 = 25$

→ select minimum value from each column and subtract that minimum value from all the column.

36 → The cost Reduction is 25

→ Now we ~~have~~ taking reduced matrix

$$
\begin{array}{c|ccccc}
 & 1 & 2 & 3 & 4 & 5 \\
\hline
1 & \infty & 10 & 17 & 0 & 1 \\
2 & 12 & \infty & 11 & 2 & 0 \\
3 & 0 & 3 & \infty & 0 & 2 \\
4 & 15 & 3 & 12 & \infty & 0 \\
5 & 11 & 0 & 0 & 12 & \infty
\end{array}
$$

→ make the 1st row and 2nd column all values are ∞ then 2 to 1 is also ∞

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$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & 10 & 17 & 0 & 1 \\ 2 & 12 & \infty & 11 & 2 & 0 \\ 3 & 0 & 3 & \infty & 0 & 2 \\ 4 & 15 & 3 & 12 & \infty & 0 \\ 5 & 11 & 0 & 0 & 12 & \infty \end{array} \Longrightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \infty & \infty & 11 & 2 & 0 \\ 3 & 0 & \infty & \infty & 0 & 2 \\ 4 & 15 & \infty & 12 & \infty & 0 \\ 5 & 11 & \infty & 0 & 12 & \infty \\ & 0 & & 0 & 0 & 0 \end{array} \begin{array}{l} \\ \\ 0 \\ 0 \\ 0 \\ 0 \\ \Rightarrow 0 \end{array}$$

(a) path (1, 2), node 2

cost $c = c(1,2) + r + \hat{r}$

$= 10 + 25 + 0 = 35$

→ Next, make the 1st row & 3rd column all values are ∞ & 3 to 1 is also ∞

$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & 10 & 17 & 0 & 1 \\ 2 & 12 & \infty & 11 & 2 & 0 \\ 3 & 0 & 3 & \infty & 0 & 2 \\ 4 & 15 & 3 & 12 & \infty & 0 \\ 5 & 11 & 0 & 0 & 12 & \infty \end{array} \Longrightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \cancel{12}\,11 & \infty & \infty & 2 & 0 \\ 3 & \infty & 3 & \infty & 0 & 2 \\ 4 & \cancel{15}\,4 & 3 & \infty & \infty & 0 \\ 5 & \cancel{11}\,10 & 0 & \infty & 12 & \infty \\ & 11 & 0 & & 0 & 0 \end{array} \begin{array}{l} \\ 0 \\ 0 \\ 0 \\ 0 \\ \Rightarrow 11 \end{array}$$

(b) Path (1, 3) Node 3

cost $c = c(1,3) + r + \hat{r}$

$= 17 + 25 + 11 = 53$

→ next make 1st row & 4th column all values are ∞ & 4 to 1 is also ∞

→ Path (1, 4) Node 4

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$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & 10 & 17 & 0 & 1 \\ 2 & 12 & \infty & 11 & 2 & 0 \\ 3 & 0 & 3 & \infty & 0 & 2 \\ 4 & 15 & 3 & 12 & \infty & 0 \\ 5 & 11 & 0 & 0 & 12 & \infty \end{array} \Longrightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & 12 & \infty & 11 & \infty & 0 \\ 3 & 0 & 3 & \infty & \infty & 2 \\ 4 & \infty & 3 & 12 & \infty & 0 \\ 5 & 11 & 0 & 0 & \infty & \infty \\ & 0 & 0 & 0 & 0 & \end{array} \begin{array}{c} \\ 0 \\ 0 \\ 0 \\ 0 \\ \Rightarrow 0 \end{array}$$

(C) Path (1,4), Node 4

$$\text{cost} = c(1,4) + \hat{r} + \hat{r}$$
$$= 0 + 25 + 0 = 25$$

→ Next make 1st row & 5th column all values are ∞ and 5 to 1 is also ∞.

$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & 10 & 17 & 0 & 1 \\ 2 & 12 & \infty & 11 & 2 & 0 \\ 3 & 0 & 3 & \infty & 0 & 2 \\ 4 & 15 & 3 & 12 & \infty & 0 \\ 5 & 11 & 0 & 0 & 12 & \infty \end{array} \Longrightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \cancel{12}\,10 & \infty & \cancel{11}\,9 & \cancel{2}\,0 & \infty \\ 3 & 0 & 3 & \infty & 0 & \infty \\ 4 & \cancel{15}\,12 & \cancel{3}\,0 & \cancel{12}\,9 & \infty & \infty \\ 5 & \infty & 0 & 0 & 12 & \infty \\ & 0 & 0 & 0 & 0 & \end{array} \begin{array}{c} \\ 2 \\ 0 \\ 3 \\ 0 \\ =5 \end{array}$$

(d) Path (1,5), Node 5

$$\text{cost} = c(1,5) + \hat{r} + \hat{r}$$
$$= 1 + 25 + 5 = 31$$

→ Now, select Path (1,4) & Node 2 matrix because it is the least cost

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→ make 4th row & 2nd column all values are ∞ & vertex 2 to 4 is also ∞ & 4 to 1 is also ∞.

$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & 12 & \infty & 11 & \infty & 0 \\ 3 & 0 & 3 & \infty & \infty & 2 \\ 4 & \infty & 3 & 12 & \infty & 0 \\ 5 & 11 & 0 & 0 & \infty & \infty \end{array} \Rightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \infty & \infty & 11 & \infty & 0 \\ 3 & 0 & \infty & \infty & \infty & 2 \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & 11 & \infty & 0 & \infty & \infty \\ & 0 & & 0 & & 0 \end{array} \begin{array}{l} \\ 0 \\ 0 \\ \\ 0 \\ \Rightarrow 0 \end{array}$$

Path (1,4,2) node 6

$$\text{cost} = \text{cost}(4,2) + r + \hat{r}$$
$$= 3 + 25 + 0 = 28$$

⇒ make 4th row & 3rd column all values are ∞ & vertex 3 to 1 is also ∞

$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \cancel{12}\,1 & \infty & \infty & \infty & 0 \\ 3 & \infty & \cancel{3}\,1 & \infty & \infty & \cancel{2}\,0 \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & \cancel{11}\,0 & 0 & \infty & \infty & \infty \\ & 11 & 0 & & & 0 \end{array} \begin{array}{l} \\ 0 \\ 2 \\ \\ 0 \\ \Rightarrow 11+2=13 \end{array}$$

$$\text{cost} = \text{cost}(4,3) + r + \hat{r}$$
$$= 12 + 25 + 13 = 50$$

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→ make 4th row & 5th column all values are ∞ & 5 to 1 is also ∞

$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & 12 & \infty & 11 & \infty & 0 \\ 3 & 0 & 3 & \infty & \infty & 2 \\ 4 & \infty & 3 & 12 & \infty & 0 \\ 5 & 11 & 0 & 0 & \infty & \infty \end{array} \Rightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \cancel{12}\,1 & \infty & \cancel{11}\,0 & \infty & \infty \\ 3 & 0 & 3 & \infty & \infty & \infty \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & \infty & 0 & 0 & \infty & \infty \\ & 0 & 0 & 0 & & \end{array} \begin{array}{l} \\ 11 \\ 0 \\ \\ 0 \\ \Rightarrow 11 \end{array}$$

Path (1, 4, 5) node 5

$$\text{cost} = \text{cost}(4,5) + r + \hat{r}$$

$$= 0 + 25 + 11 = 36$$

⟹ select Path (1, 4, 2), Node 6

⟹ make 2nd row & 3rd column all values are ∞.

$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \infty & \infty & 11 & \infty & 0 \\ 3 & 0 & \infty & \infty & \infty & 2 \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & 11 & \infty & 0 & \infty & \infty \end{array} \Rightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \infty & \infty & \infty & \infty & \infty \\ 3 & 0 & \infty & \infty & \infty & \cancel{2}\,0 \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & \cancel{11}\,0 & \infty & \infty & \infty & \infty \\ & 0 & & & & \end{array} \begin{array}{l} \\ \\ 0 \\ \\ 11 \\ \Rightarrow 11+2=13 \end{array}$$

Path (1, 4, 2, 3) Node 9

$$\text{cost} = \text{cost}(2,3) + \overset{(16)}{r} + \hat{r}$$

$$= 11 + 28 + 13 = 52$$

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⇒ make 2nd row & 5th column all values are ∞ & 5 to 1 is also ∞.

$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \infty & \infty & 11 & \infty & 0 \\ 3 & 0 & \infty & \infty & \infty & 2 \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & 11 & \infty & 0 & \infty & \infty \end{array} \Rightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \infty & \infty & \infty & \infty & \infty \\ 3 & 0 & \infty & \infty & \infty & \infty \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & \infty & \infty & 0 & \infty & \infty \\ & 0 & & 0 & & \end{array} \begin{array}{l} \\ \\ 0 \\ \\ 0 \\ \Rightarrow 0 \end{array}$$

Path (1, 4, 2, 5) Node 10

$$\text{cost} = \text{cost}(2,5) + c(6) + \hat{r}$$

$$= 0 + 28 + 0 = 28$$

→ select the path of matrix (1, 4, 2, 5) & Node 10

→ make 5th row & 3rd column all values are ∞

$$\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \infty & \infty & \infty & \infty & \infty \\ 3 & 0 & \infty & \infty & \infty & \infty \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & \infty & \infty & \infty & \infty & \infty \end{array} \Rightarrow \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & \infty & \infty & \infty & \infty & \infty \\ 2 & \infty & \infty & \infty & \infty & \infty \\ 3 & \infty & \infty & \infty & \infty & \infty \\ 4 & \infty & \infty & \infty & \infty & \infty \\ 5 & \infty & \infty & \infty & \infty & \infty \end{array}$$

Path (1, 4, 2, 5, 3) Node 11

$$\text{Cost} = \text{cost}(5,3) + c(5) + \hat{r}$$

$$= 0 + 28 + 0 = 28$$

$$\boxed{1-4-2-5-3-1}$$

The cost of tour is 28.

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