

# Efficient Algorithms

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# Lecture 14: State Space Search

- Brute Force
- Backtracking
- Branch & Bound

# Subset Sum

**Definition:** Given a multi-set  $D = \{d_1, d_2, \dots, d_n\}$ , where  $\forall d_i \geq 0$ , and a target value  $k$ , find  $S \subseteq D$  such that the sum of the elements in  $S$  equals  $k$ .

**Example:**  $D = \{1, 4, 1, 9, 7\}$  and  $k = 11$

Then, we have  $S = \{1, 1, 9\}, \{4, 7\}$ .

# Subset Sum: NP-Hard

We can show the **NP-completeness** of the decision version of *SubsetSum* by reducing from 3SAT:

$$3SAT \leq_p \textit{SubsetSum}$$

Thus, the search version of *SubsetSum* must be at least as hard as the decision version.

# Subset Sum: Subset Enumeration

To enable us to search for solution to *SubsetSum*, we must decide on a **format** in which solutions  $S$  are represented.

We can **enumerate** all the possible subsets  $S$  using a **bit vector**.

Suppose  $x[1 \dots n]$  is a bit vector of length  $n$ .

$$x[i] = 1 \quad \text{iff} \quad d_i \in S$$

$$x[i] = 0 \quad \text{iff} \quad d_i \notin S$$

# Subset Enumeration

Suppose  $x[1 \dots n]$  is a bit vector of length  $n$ .

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**Example:**  $D = \{1, 4, 1, 9, 7\}$  and  $k = 11$ .

$S = \{1, 1, 9\}$  can be represented with  $x = \{1, 0, 1, 1, 0\}$ .

$S = \{4, 7\}$  can be represented with  $x = \{0, 1, 0, 0, 1\}$ .

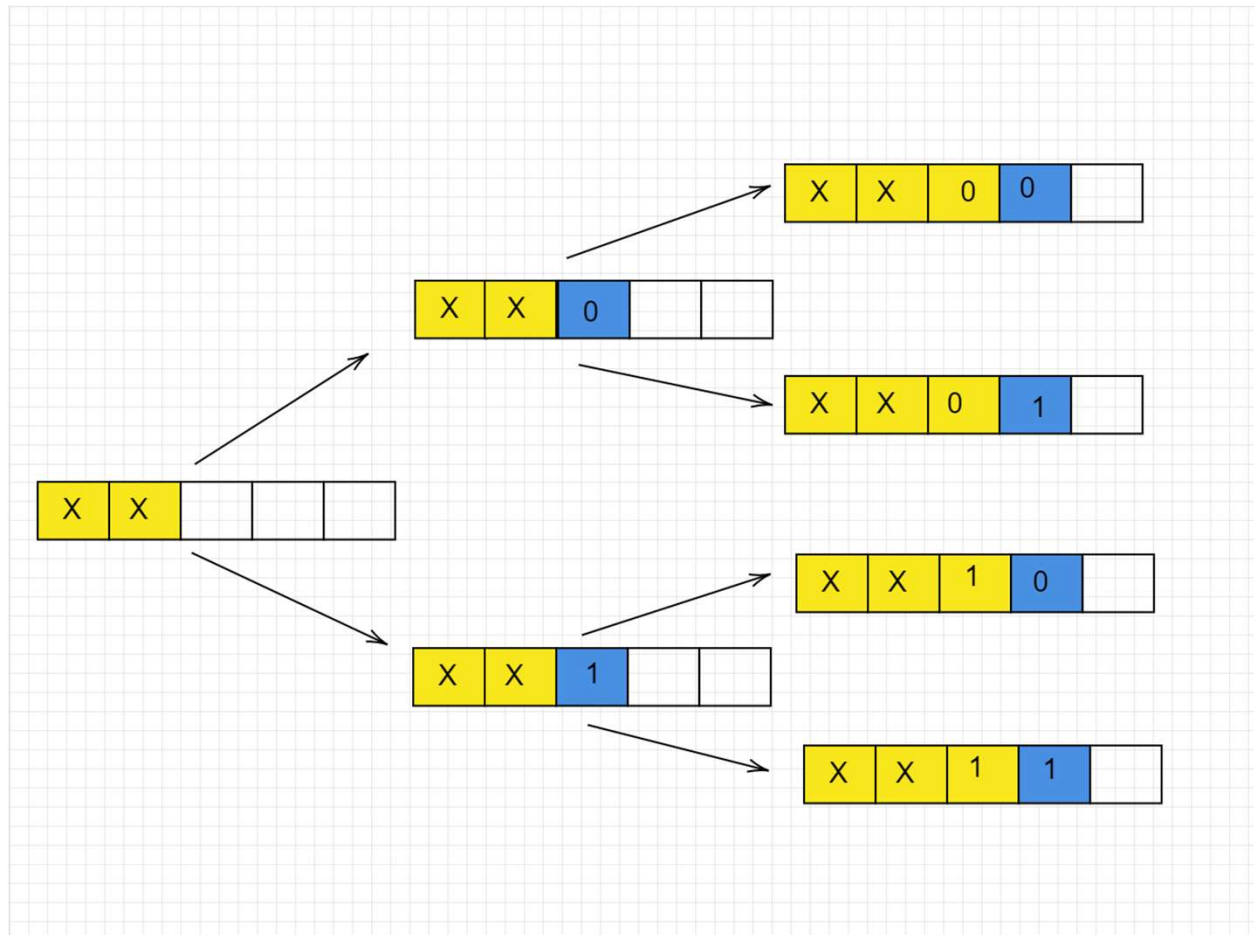
## Subset Enumeration: Binary Counter

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```
1: procedure BINARY-COUNT( $x[1..n], m$ )
2:   if  $m == n$  then
3:     PRINT( $x$ )
4:   else
5:      $x[m + 1] = 0$ 
6:     BINARY-COUNT( $x, m + 1$ )
7:      $x[m + 1] = 1$ 
8:     BINARY-COUNT( $x, m + 1$ )
```

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# Subset Enumeration: Binary Counter





# DFS and BFS

We can *enumerate* and *evaluate* solutions using

- Depth-First Search (*DFS*)
- Breadth-First Search (*BFS*)

DFS or BFS visits graphs or trees generated *at runtime* by the algorithm in question:

- Each state is represented by a vertex
- A decision is represented by an edge connecting one state to another adjacent state

If DFS is implemented via *recursion*, *stack frames* can represent *states*, generated by corresponding *recursive calls*.

## Subset Sum: Recursive DFS

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```
1: procedure SUBSET-SUM( $d[1..n], k, x[1..n], m$ )
2:   if  $m == n$  then
3:     if SUM( $d, x$ ) ==  $k$  then
4:       PRINT( $x$ )
5:   else
6:      $x[m + 1] = 0$ 
7:     SUBSET-SUM( $d, k, x, m + 1$ )
8:      $x[m + 1] = 1$ 
9:     SUBSET-SUM( $d, k, x, m + 1$ )
```

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## Subset Sum: Iterative DFS

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```
1: procedure SUBSET-SUM( $d[1..n], k$ )
2:    $S = \text{new Stack}$ 
3:    $S.\text{push}([])$ 
4:   while  $S \neq \emptyset$  do
5:      $x[1..m] = S.\text{pop}()$ 
6:     if  $m == n$  then
7:       if SUM( $d, x$ ) ==  $k$  then
8:         PRINT( $x$ )
9:     else
10:       $x_0 = \text{COPY}(x, m + 1)$ 
11:       $x_0[m + 1] = 0$ 
12:       $x_1 = \text{COPY}(x, m + 1)$ 
13:       $x_1[m + 1] = 1$ 
14:       $S.\text{push}(x_1)$ 
15:       $S.\text{push}(x_0)$ 
```

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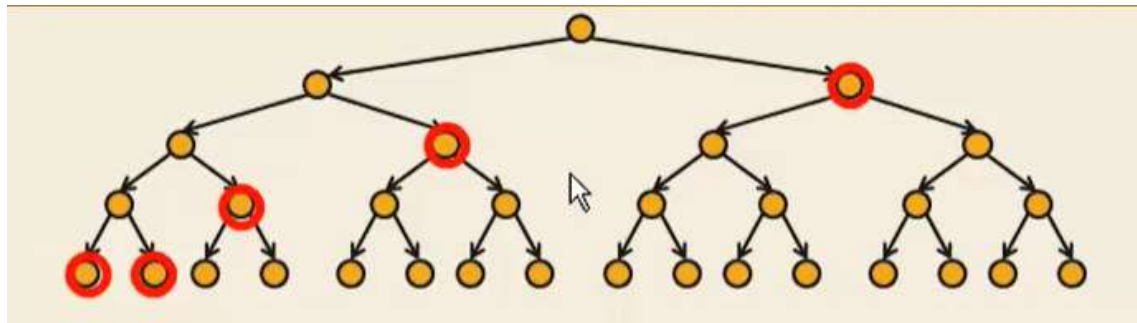
## Subset Sum: BFS

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```
1: procedure SUBSET-SUM( $d[1..n], k$ )
2:    $Q = \text{new Queue}$ 
3:    $Q.\text{enqueue}([])$ 
4:   while  $Q \neq \emptyset$  do
5:      $x[1..m] = Q.\text{dequeue}()$ 
6:     if  $m == n$  then
7:       if  $\text{SUM}(d, x) == k$  then
8:          $\text{PRINT}(x)$ 
9:     else
10:       $x_0 = \text{COPY}(x, m + 1)$ 
11:       $x_0[m + 1] = 0$ 
12:       $x_1 = \text{COPY}(x, m + 1)$ 
13:       $x_1[m + 1] = 1$ 
14:       $Q.\text{enqueue}(x_0)$ 
15:       $Q.\text{enqueue}(x_1)$ 
```

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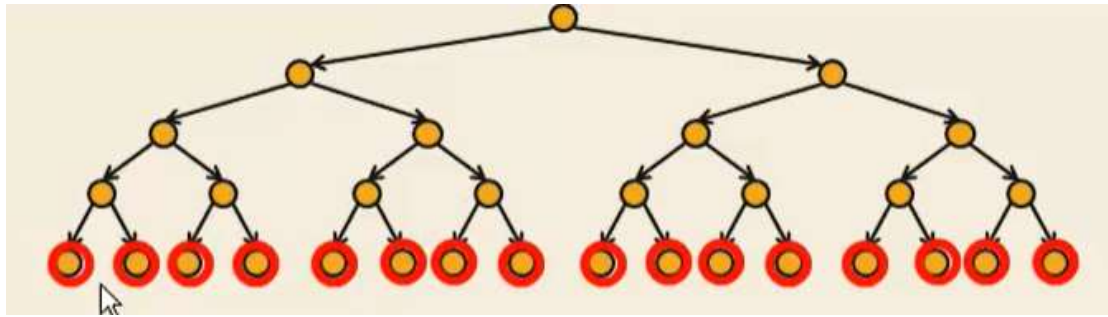
# DFS: Memory Consumption



Suppose a search tree has a **branching factor**  $b$  and **height**  $h$ .

The **space complexity** is determined by the maximum number of states kept on the stack at any given point in time, which is  $O(bh)$ .

# BFS: Memory Consumption



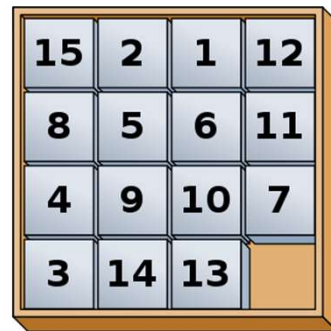
Suppose a search tree has a **branching factor**  $b$  and **height**  $h$ .

The **space complexity** is determined by the maximum number of states kept on the stack at any given point in time, which is  $O(b^h)$ .

# 15-Puzzle

Given the following instance of the 15-Puzzle, we would like to solve the puzzle in the ***fewest number of moves*** possible.

Which graph traversal technique would you choose? BFS or DFS?

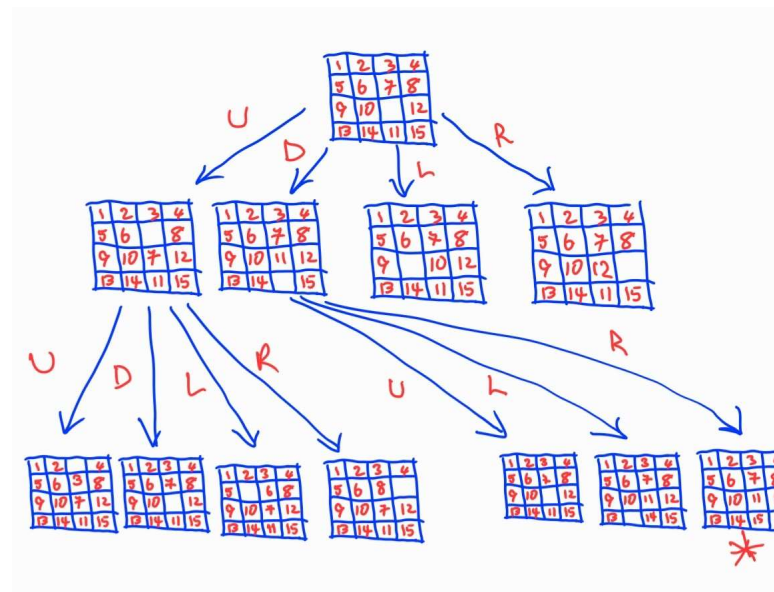


15	2	1	12
8	5	6	11
4	9	10	7
3	14	13	

# 15-Puzzle

Recall that BFS always finds a shortest path from a starting vertex to each reachable vertex in a graph.

Therefore, BFS will solve the 15-Puzzle in the ***fewest*** number of moves.





# M3D2

Given a target value  $k$ , find a way from the initial value of 1 to get to  $k$  by performing only the following **two operations** successively:

- **Multiplication by 3** (M3)
- **Division by 2** (D2)

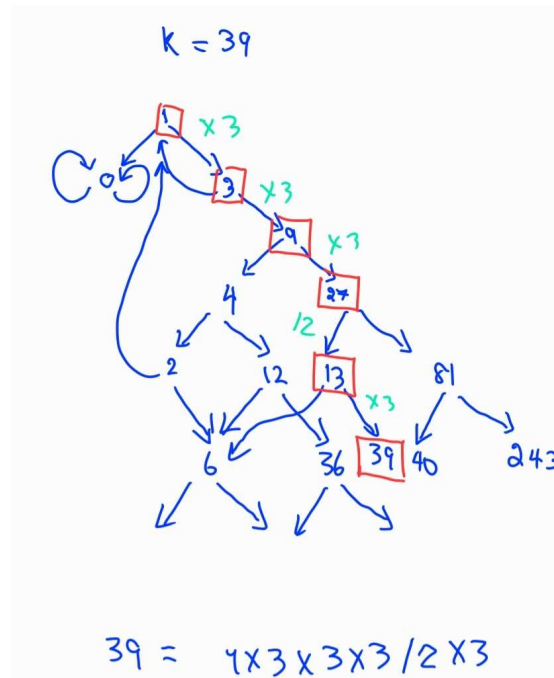
**Example:**  $k = 41$

$41 =$

$1 \times 3 \times 3 / 2 / 2 \times 3 \times 3 \times 3 \times 3 / 2 / 2 / 2 / 2 \times 3 / 2 \times 3 \times 3 / 2 \times 3 / 2$   
 $/ 2 / 2 \times 3 / 2 / 2 \times 3 \times 3 / 2 \times 3 \times 3 \times 3 \times 3 / 2 / 2 / 2 / 2 \times 3 / 2 / 2$   
 $/ 2 / 2 \times 3 / 2 \times 3 / 2 \times 3 / 2 \times 3 / 2 / 2$

## M3D2: BFS

BFS yields the *minimum* number of operations possible to get to the target value  $k$  if there exists a way to get to  $k$ .

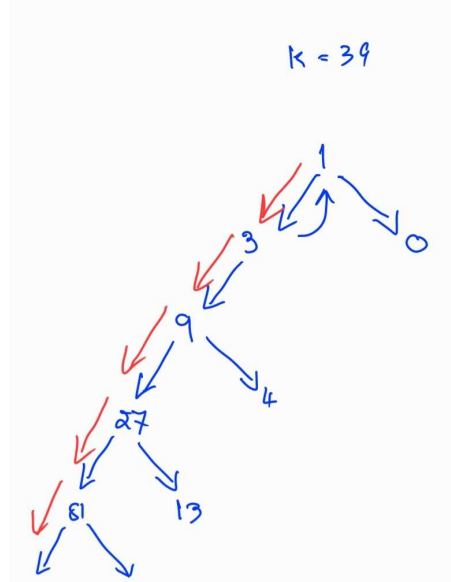


$$39 = 1 \times 3 \times 3 \times 3 / 2 \times 3$$

## M3D2: DFS

**Caveat:** With the **wrong** state space design, DFS may not terminate on some inputs.

**Example:** Given  $k = 39$ , we choose to perform *M3* before *D2*.



# DFS vs BFS: Pros & Cons

## **DFS**

- may not terminate on some inputs for infinite state-space graphs
- uses only  $O(bh)$  stack space

## **BFS**

- always yields a solution closest to the initial state
- uses only  $O(b^h)$  queue space

**Both approaches** are bound to run **extremely slowly** for **large** state space trees/graphs.

- Memory can potentially run out before reaching a solution if any exists !!!

# Backtracking

Exploring every solution state can be *exponentially slow* for *large* state-space graphs.

By *intelligently* considering each *partial solution state*, we can sometimes avoid the need to go further down some subtrees that cannot contain *answer states*.

Upon detecting such situations, we immediately *backtrack* and move on to look elsewhere.

# Subset Sum

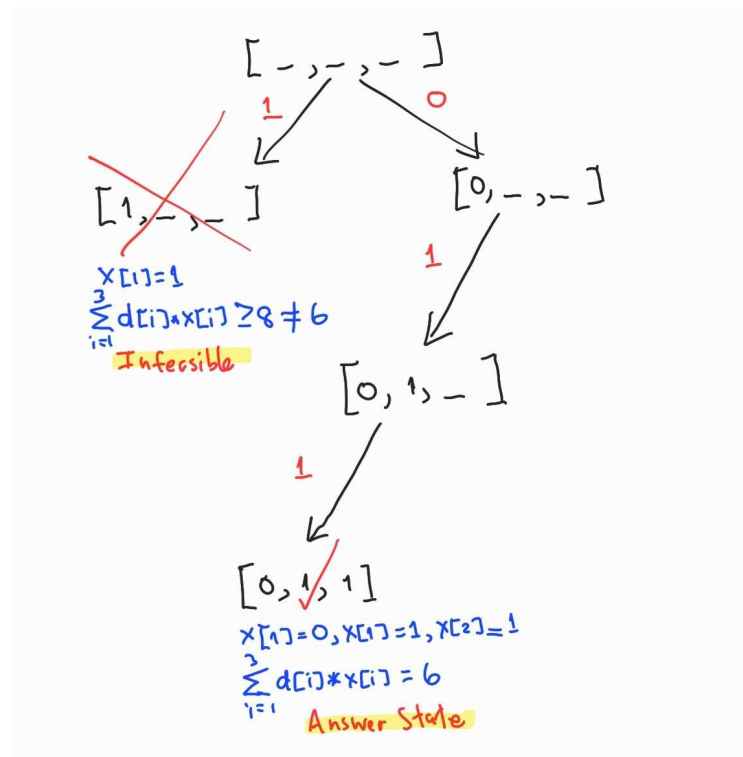
Let us revisit *SubsetSum*.

**Example:**  $D = \{8, 2, 4\}$  and  $k = 6$

Suppose we fill the bitvector  $x$  with 1 before 0 and explore the state-space graph using DFS.

Upon exploring the partial solution state  $[1, \_ \_]$ , we can be sure that the sum can never be 6 if 8 is included, since 8 is already ***strictly greater than*** 6.

# Subset Sum: Backtracking with DFS



# Subset Sum: Backtracking with DFS

Backtracking occurs in *lines 3-4*.

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```
1: procedure SUBSET-SUM( $d[1...n], k, x[1...n], m$ )
2:    $sum = \text{SUM}(d, x, m)$ 
3:   if  $sum > k$  then
4:     return
5:   if  $m == n$  then
6:     if  $sum == k$  then
7:       PRINT( $x$ )
8:     else
9:        $x[m + 1] = 1$ 
10:      SUBSET-SUM( $d, k, x, m + 1$ )
11:       $x[m + 1] = 0$ 
12:      SUBSET-SUM( $d, k, x, m + 1$ )
```

---



# Subset Sum: Backtracking with BFS

Backtracking occurs when the if-statement evaluates to *false* in *line 7*.

---

```
1: procedure SUBSET-SUM( $d[1..n]$ ,  $k$ )
2:    $Q = \text{new Queue}$ 
3:    $Q.\text{enqueue}([])$ 
4:   while  $Q \neq \emptyset$  do
5:      $x[1..m] = Q.\text{dequeue}()$ 
6:      $\text{sum} = \text{SUM}(d, x, m)$ 
7:     if  $\text{sum} \leq k$  then
8:       if  $m == n$  then
9:         if  $\text{SUM}(d, x) == k$  then
10:          PRINT( $x$ )
11:       else
12:          $x_0 = \text{COPY}(x, m + 1)$ 
13:          $x_0[m + 1] = 0$ 
14:          $x_1 = \text{COPY}(x, m + 1)$ 
15:          $x_1[m + 1] = 1$ 
16:          $Q.\text{enqueue}(x_0)$ 
17:          $Q.\text{enqueue}(x_1)$ 
```

---

# Backtracking: Lesson Learned

**Backtracking** can help **prune** a potentially large state-space graph, thereby cutting down on those **exponentially many** vertices corresponding to **infeasible solutions**.

**Backtracking** can be combined with **DFS** or **BFS** to improve the **running time** as well as **memory consumption** in a number of **NP-Hard search problems** whose objectives are to find solutions that satisfy the given constraints.

# Branch & Bound

**Branch & Bound** can help improve both the running time and the memory consumption in algorithms involving **NP-Hard optimization problems** in a similar manner to **Backtracking**, which helps improve the running time and memory consumption in algorithms involving **search problems**.

We can incorporate both **Branch & Bound** and **Backtracking** to solve optimization problems.

# 0/1 Knapsack Problem

Given a set  $S$  of  $n$  different items, each item is associated with a weight  $w_i$  and a value  $v_i$ , the goal is to pick items in such a way that maximizes the total value  $V$  and satisfies the capacity constraint  $W$ :

$$\begin{aligned} &\text{Maximize } V = \sum_{k=1}^n x_k v_k \\ &\text{subject to } \sum_{k=1}^n x_k w_k \leq W \\ &\quad x_k \in \{0,1\} \end{aligned}$$

# 0/1 Knapsack Problem

*0/1 Knapsack* can be solved using *dynamic programming*.

The running time is  $O(nW)$ , which is pseudo-polynomial.

In fact, *0/1 Knapsack* is an *NP-Hard* optimization problem.

Thus, an algorithm that can solve *0/1 Knapsack* in polynomial time has not been discovered so far.

# 0/1 Knapsack Problem

To apply **Branch & Bound**, we need to associate a **bound** to each **partial solution state**.

There can be a number of schemes that can be used to compute bounds. Some schemes might provide **tighter bounds** than others.

Ones that provide tighter bounds can potentially **prune more subtrees** and hence be more efficient both in terms of running time and memory consumption.

## 0/1 Knapsack Problem: Example

	weight	value
Item 1	3	21
Item 2	6	30
Item 3	5	15
Item 4	10	20
Item 5	8	8

## 0/1 Knapsack Problem: Example

**Scheme:** Assume that we can take all the **undecided** items.

Suppose that we have decided on the first  $k - 1$  items.

If item  $k$  is included, the upper bound  $UB$  remains the same whereas the remaining capacity is updated:

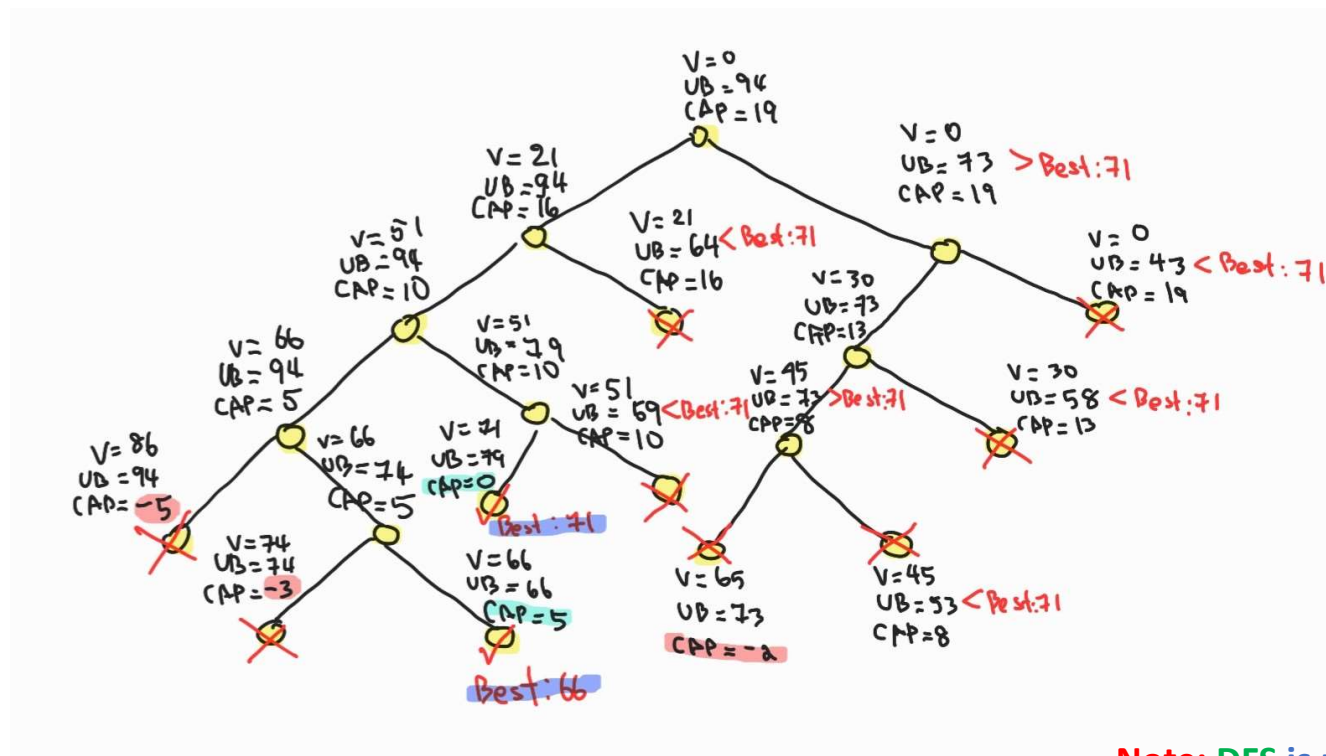
$$CAP := CAP - w_k$$

If item  $k$  is **not** included, the remaining capacity remains the same whereas the upper bound is updated:

$$UB := UB - v_k$$



# 0/1 Knapsack Problem: Example



**Note:** DFS is used to perform the state space search.

## 0/1 Knapsack Problem:

A better scheme that can provide tighter upper bounds is to use the *optimal values* from the *Fractional Knapsack Problem* as *upper bounds*.

Since *Fractional Knapsack* exhibits *optimal substructure* and *greedy choice*, we can find the optimal value using the greedy strategy of choosing one with the maximum value per unit, and the algorithm runs in polynomial time in the number of items  $n$ .

# Branch & Bound : Lessons Learned

**Branch & Bound** can help prune subtrees that contain only solutions that cannot be better than the best solution found.

We decide whether to go down any given subtree by comparing the **current best solution** with the upper bound of the root vertex of that subtree.

Although there exists some computational overhead in computing an upper bound at each vertex, if that overhead is **reasonably small** relative to the number of solution states that can be potentially pruned, such an **upper-bound scheme** should be worth trying.

# Summary

In this lecture, we covered the following state-space search techniques for solving NP-Hard and NP-complete problems:

- Brute-Force Search
- Backtracking
- Branch & Bound

In the next lecture, we will cover ***Randomized Algorithms***.