



BABEȘ-BOLYAI UNIVERSITY

Faculty of Mathematics and Computer Science



Algorithms and Programming

Lecture 11 – Problem solving methods (II)

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Course content

Programming in the large

- Introduction in the software development process
- Procedural programming
- Modular programming
- Abstract data types
- Software development principles
- Testing and debugging

Programming in the small

- Recursion
- Complexity of algorithms
- Search and sorting algorithms
- **Problem solving methods**
 - Generate and test, Backtracking, Divide et impera
 - **Dynamic programming, Greedy**
- Recap

Last time

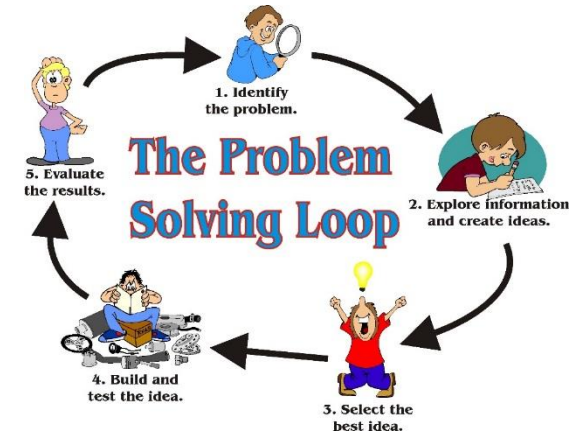
- Problem solving methods
 - Types
 - Techniques
 - Exact methods
 - Heuristic methods
 - Algorithms
 - Backtracking
 - Divide and conquer

Today

- Exact methods
 - Dynamic programming
- Heuristics methods
 - Greedy algorithms

Recap: the problem solving loop

- Step in solving a problem
 - Problem definition
 - Problem analysis
- Choose problem solving technique
 - **Search**
 - Knowledge representation
 - Abstraction



Problem solving by search

- Solving problems by search using standard methods
 - Exact methods
 - **Generate and test**
 - **Backtracking**
 - **Divide and conquer**
 - **Dynamic programming**
 - Heuristic methods
 - **Greedy method**

Dynamic Programming (DP)

- Basic idea:
 - Break the problem in overlapping sub-problems which are similar to the initial problem but are smaller in size
 - Solve the sub-problems
 - Compute the final solution by combining the sub-solutions
- Applicable in solving problems where:
 - Problems where one needs to find the best decisions one after another
 - The solution is the result of a sequence of decisions $dec_1; dec_2; \dots; dec_n$.
 - The principle of optimality holds (whatever the initial state is remaining decisions must be optimal with regard the state following from the first decision)

DP: Mechanism

- Break the problem in nested sub-problems $P(P_1(P_2(P_3(\dots(P_n))\dots))\dots)$
- Solve the most inner sub-problem P_n and store the partial result
- Solve the sub-problem P_{n-1} based on the solution found for sub-problem P_n and store the partial result
- Solve the sub-problem P_{n-2} based on the solution found for sub-problem P_{n-1} and store the partial result
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- Solve the sub-problem P_1 based on the solution found for sub-problem P_2 and store the partial result
- Solve the problem P based on the solution found for sub-problem P_1 and store the **final** result

Dynamic Programming

- When DP can be used?
 - Problem P (optimization problem) with input data D can be solved by solving the same problem P but with input data d, where $d < D$
 - Solution is the result of a sequence of decisions dec1, dec2, ...
 - The problem can be divided in overlapping problems
 - The solutions of the sub-problems can be stored for future uses
 - The principle of optimality
- Features
 - Always gives the optimal solution
 - Polynomial run time

Dynamic Programming

- Notations
- We consider states s_0, s_1, \dots, s_n
 - s_0 is the initial state
 - s_n is the final state
 - States are obtained by successively applying the sequence of decisions $dec_1, dec_2, \dots, dec_n$ (using the decision d_i we pass from state s_{i-1} to state s_i)

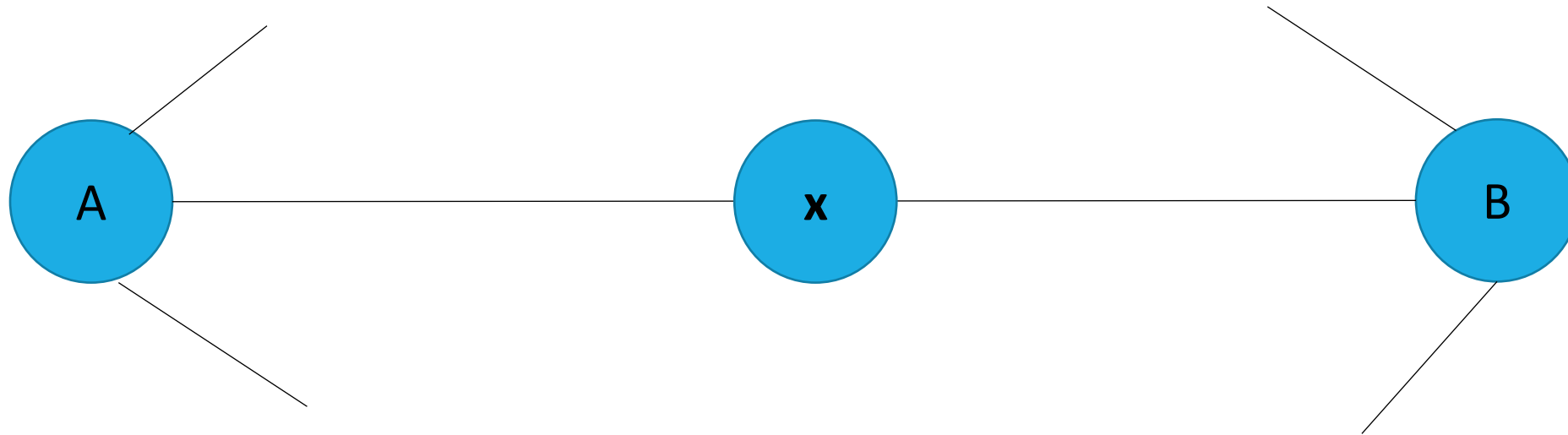


DP: Principle of optimality

- Principle of optimality
 - The general optimum implies the local / partial optimum
 - In an optimal sequence of decisions, each decision is optimum
 - The principle does not hold true for any problem
- Formally, a sequence of decisions $dec_1, dec_2, \dots, dec_n$ optimally leads from state s_0 to state s_n if at least one of the following conditions is satisfied:
 - $dec_k, dec_{k+1}, \dots, dec_n$ is a sequence of decisions that optimally leads from state s_{k-1} to state s_n for any $k, 1 \leq k \leq n$ (**forward** method)
 - $dec_1, dec_2, \dots, dec_k$ is a sequence of decisions that optimally leads from state s_0 to state s_k for any $k, 1 \leq k \leq n$ (**backward** method)
 - dec_{k+1}, \dots, dec_n and $dec_1, dec_2, \dots, dec_k$ are two sequences of decisions that optimally lead from state s_{k-1} to state s_n and from state s_0 to state s_k for any $k, 1 \leq k \leq n$ (**mixed** method)

Principle of optimality

- In solving a problem, we have to make a sequence of n decisions
- If this sequence is optimal then the last k decisions ($1 < k < n$) must be optimal



DP: Algorithm

- Verify the principle of optimality
- Establish the structure of the solution
 - Break the problem in sub-problems
 - Overlapping sub-problems – break down the problem into sub-problems which are reused multiple times
- Memoization
 - Store the solutions to the sub-problems for later use
- Based on the principle of optimality, the value of the optimal solution is recursively defined
- The value of the optimal solution is computed in a bottom-up manner, starting from the smallest cases for which the value of the solution is known

DP: Example

- **Problem:** find the longest increasing subsequence from a list of integer numbers.

i	1	2	3	4	5
list	2	1	9	6	12

- **Solution**
 - For each i, calculate the length of the longest increasing subsequence that can be formed
 - In the end, select the element where the longest subsequence is formed

i	1	2	3	4	5
list	2	1	9	6	12
L	3 2,9,12 sau 2,6,12	3 1,9,12 sau 1,6,12	2 9,12	2 6,12	1 12

DP: Example

- **Problem:** find the longest increasing subsequence from a list of integer numbers.

i	1	2	3	4	5
list	2	1	9	6	12

- Step 1: The principle of optimality
 - The principle of optimality is verified in its forward variant
 - The longest subsequence that starts at position i has k elements \Rightarrow the subsequences that can be formed from it (with $k-1$, $k-2$, ... elements) are increasing subsequences and have maximal length

DP: Example

- **Problem:** find the longest increasing subsequence from a list of integer numbers.

i	1	2	3	4	5
list	2	1	9	6	12

- Step 2: The structure of the optimal solution
 - Break the problem in sub-problems
 - **Problem:** determine the longest increasing subsequence
 - **Sub-problem:** determine the longest increasing subsequences that starts with $\text{list}[i]$ for $i = n, n-1, n-2, \dots, 1$. These subsequences have the length at most $1, 2, \dots, n$.
 - **Solution:** the longest subsequence from the n subsequences.

DP: Example

i	1	2	3	4	5
list	2	1	9	6	12

- **Problem:** longest increasing subsequence
- Step 3: Determine the global optimum based on the partial optimas
 - Let L_i be the length of the longest subsequence that starts with $\text{list}[i]$
 - The increasing sub-sequences that start with $\text{list}[i]$ are obtained by adding the element $\text{list}[i]$ in front of an increasing subsequence that starts with $\text{list}[j]$ if $\text{list}[i] \leq \text{list}[j]$

$$L_i = 1 + \max_{j=i+1, n} \{L_j, \text{list}[i] \leq \text{list}[j]\}, \text{ for } i = n - 1, \dots, 1$$

- $L_n = 1$

- **Optimal solution:** $L_{\max} = \max_{i=1, n} \{L_i\}$

```

def long_seq(s):
    L = [0] * len(s)
    ind = [0] * len(s) #index of the successor of list[i] in the long seq
    #compute vector L
    L[len(s) - 1] = 1
    ind[len(s) - 1] = -1
    for i in range(len(s) - 2, -1, -1):
        ind[i] = -1
        L[i] = 1
        for j in range(i+1, len(s)):
            if (s[i] <= s[j]):
                if (L[i] <= L[j] + 1):
                    L[i] = L[j] + 1
                    ind[i] = j

    #determine position max elem from L
    max_pos = 0
    for i in range(1, len(s)):
        if (L[i] > L[max_pos]):
            max_pos = i

    #construct the solution
    sol = []
    i = max_pos
    while (i != -1):
        sol.append(s[i])
        i = ind[i]
    return sol

```

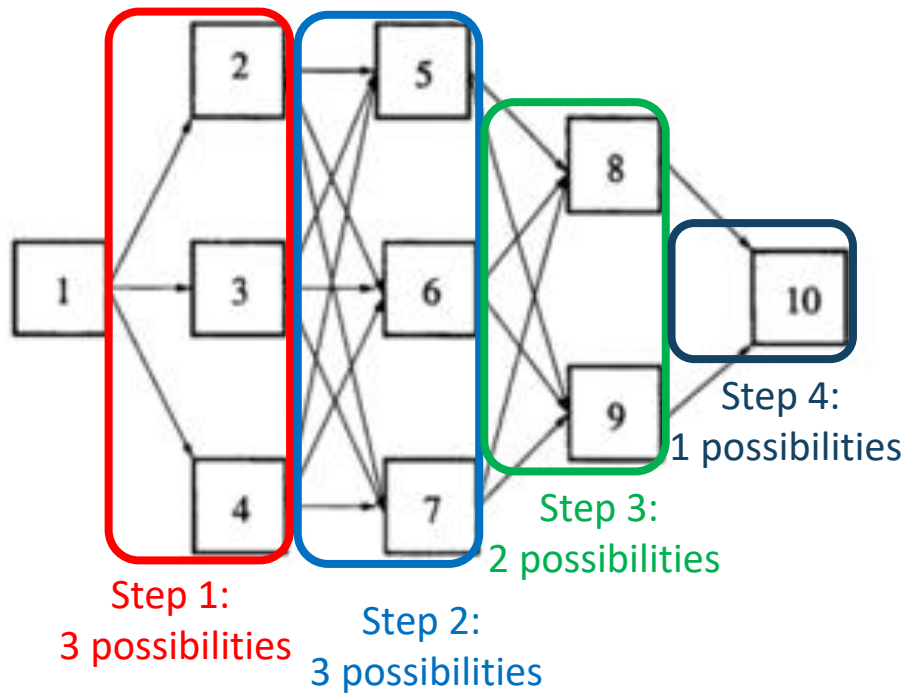
```

def test_long_seq():
    assert long_seq([2,1,9,6,12]) == [2, 6, 12]
    assert long_seq([0,-2,3,1,0,-1,2,5,-5,5,-8,10,7,-3,1]) == [0,0,2,5,5,7]

```

DP: Example 2

Stagecoach problem (*TSP with less roads due to hostile territory*)

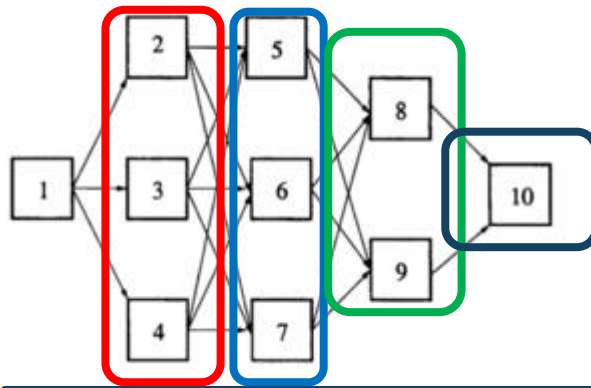


Costs:

	2	3	4		5	6	7
1	2	4	3				
				2	7	4	6
				3	3	2	4
				4	4	1	5
	8	9					
5	1	4					
6	6	3					
7	3	3					
				10			
				8	3		
				9	4		

DP: Example 2

- There are n steps
- Decision regarding state in step n is x_n
- From state s in step n choose x_n the next state: $f_n(s, x_n)$ is the cost of best decision for all remaining steps
- $x_n^*(s)$ is value of x_n that minimizes $f_n(s, x_n)$ and $f_n^*(s)$ is the minimum corresponding value
- The objective is to find $f_1^*(s)$
 - To do that, first we need to find $f_4^*(s)$, $f_3^*(s)$, $f_2^*(s)$



	2	3	4
1	2	4	3

	5	6	7
2	7	4	6
3	3	2	4
4	4	1	5

	8	9
5	1	4
6	6	3
7	3	3

	10
8	3
9	4

$$f_4^*(s) = ?$$

For which x_4 is $f_4(s, x_4)$ min?
 x_4 can be only 10 ...

s	$f_4^*(s)$	$x_4^*(s)$
8	3	10
9	4	10

$$f_2^*(s) = ?$$

$$f_2(s, x_2) = cost(s, x_2) + f_3^*(x_2)$$

s	$f_2(s, 5)$	$f_2(s, 6)$	$f_2(s, 7)$	$f_2^*(s)$	$x_2^*(s)$
2	11	11	12	11	5 or 6
3	7	9	10	7	5
4	8	8	11	8	5 or 6

$$f_3^*(s) = ?$$

$f_3(s, x_3) = cost(s, x_3) + f_4^*(x_3)$
 x_3 can be 8 or 9
 s can be 5, 6 or 7

s	$f_3(s, 8)$	$f_3(s, 9)$	$f_3^*(s)$	$x_3^*(s)$
5	4	8	4	8
6	9	7	7	9
7	6	7	6	8

$$f_1^*(s) = ?$$

s	$f_1(s, 2)$	$f_1(s, 3)$	$f_1(s, 4)$	$f_1^*(s)$	$x_1^*(s)$
1	13	11	11	11	3 or 4

Solutions (cost 11):

1 -> 3 -> 5 -> 8 -> 10

1 -> 4 -> 5 -> 8 -> 10

1 -> 4 -> 6 -> 9 -> 10

Greedy method

- Basic idea
 - Break the problem in successive sub-problems similar to the initial problem but of smaller dimensions
 - Solve the sub-problems and determine the final solution by successively selecting the best sub-solutions
 - Global optimum = a sequence of local optimas
- Mechanism
 - Divide the problem in successive sub-problems P_1, P_2, \dots, P_n
 - Progress to the final solution by selecting at each step the best decision

Greedy method

- When to use Greedy?
 - Problem P (optimization)
 - Solution is the result of a successive selections of local optima
 - Problems with solution represented by subsets or cartesian products that achieve a certain optimum (minum or maximum) of an objective function
- Features
 - Can reach the optimal solution
 - Builds the solution step by step
 - Offers a single solution (unlike backtracking)
 - Polynomial run time
- Disadvantages: Short-sighted and non-recoverable

Greedy Algorithm

- Let S be a solution to the problem and C the set of local optima for each sub-problem (candidate elements of the solution)

```
def greedy(C):  
    S =  $\emptyset$   
    while (not isSolution(S)) and (C  $\neq \emptyset$ ):  
        el = selectMostPromising(C)  
        C.remove(el)  
        if acceptable(el, S):  
            S.append(el)  
    if isSolution(S):  
        return S  
    else:  
        return None
```


Greedy - Example of Problems



- **Coins Problem**

- Consider a sum of money and a set of coins units. The problem is to establish a modality to pay the sum of money using a minimum number of coins.

- **Knapsack Problem**

- Consider a set of objects, each having a value and weight, and a knapsack able to support a total weight of W . Place in the knapsack some of the objects, such that the total weight of the objects is not larger than W and the objects have max value.

- **General Problem**

- Let us consider the given set C of candidates to the solution of a given problem P .
- The objective is to provide a subset B to fulll certain conditions (called internal conditions) and to maximize (minimize) a certain objective function.

Greedy strategy

- Greedy algorithm finds the solution in an incremental way
- Greedy strategy
 - Successively incorporate elements that realize the local optimum
 - No second thoughts are allowed on already made decisions
- Generally, the required elements of a greedy strategy are:
 - A **candidate set** (from which a solution is created)
 - A **selection function** (selects the best candidate to be added to the solution)
 - A **feasibility function** (determines if a candidate can be used in a solution)
 - An **objective function** (assigns a value to a solution, or a partial solution)
 - A **solution function** (checks if a complete solution has been found)

Greedy: Coins Problem

- **Problem:** Find a way to pay a sum of money using a minimum number of coins (different values of coins are available).
 - Data: Sum = 80, Coins = [1, 5, 10, 25, 50]
 - Results: $80 = 50 + 25 + 5$
- Data: Sum = 10, Coins = [1, 2, 3, 4]
- Results : $10 = 4 + 3 + 2 + 1$
- Data : Sum = 10, Coins = [2, 3, 4, 5]
- Results : $10 = 5 + 3 + 2$

Greedy: Example

- Solution
 - C – list of available coins
 - *isSolution(sol)*
 - If the sum of coins selected in sol is equal to the desired sum
 - *selectMostPromissing(C)*
 - Select the highest value coin in C
 - *acceptable(el,sol)*
 - If the sum of coins in sol + el is not over the desired sum

```

def sum(l):
    s = 0
    for el in l:
        s = s + el
    return s

def isSolution(solution, limit):
    return sum(solution) == limit

def selectMostPromissing(candidates):
    return max(candidates)

def acceptable(element, solution, limit):
    return sum(solution) + element <= limit

def greedy_coins(coins, sumOfMoney):
    sol = []
    while (not isSolution(sol, sumOfMoney)) and (coins != []):
        el = selectMostPromissing(coins)
        coins.remove(el)
        if acceptable(el, sol, sumOfMoney):
            sol.append(el)
    if isSolution(sol, sumOfMoney):
        return sol
    else:
        return None

```

```

def test_greedy_coins():
    assert greedy_coins([1, 5, 10, 25, 50], 80) == [50, 25, 5]
    assert greedy_coins([1, 2, 3, 4], 10) == [4, 3, 2, 1]
    #assert greedy_coins([1, 2, 3, 4, 5], 10) == [5, 3, 2]
    assert greedy_coins([2, 3, 4, 5], 10) == None

test_greedy_coins()

```

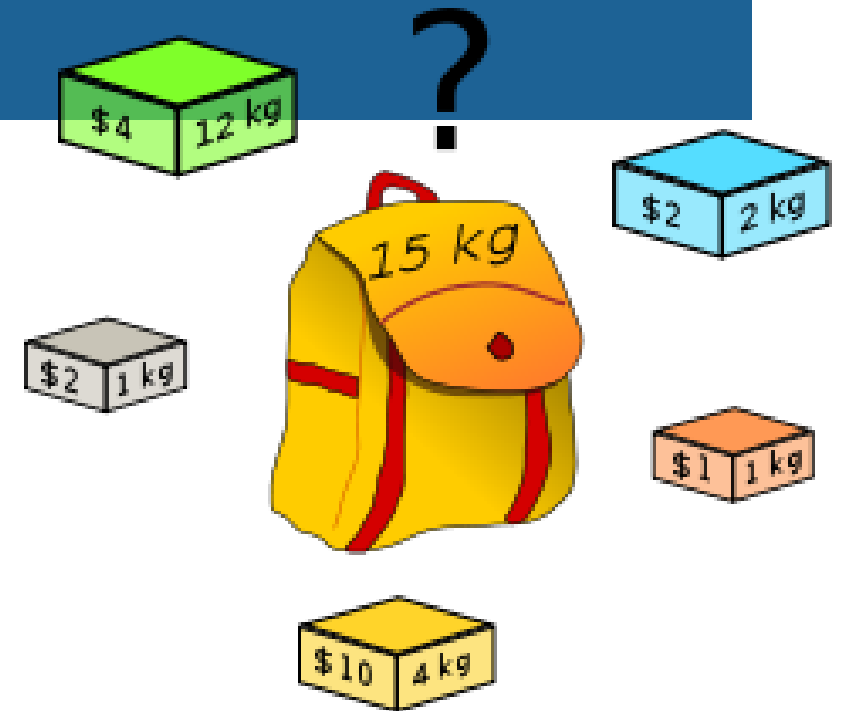
Knapsack problem

- Each object has a value (v) and a weight (w).
- Place objects of total maximum value without going over the total weight W allowed.

$$\begin{aligned} &\text{maximize } \sum_{i=1}^n v_i x_i \\ &\text{subject to } \sum_{i=1}^n w_i x_i \leq W \text{ and } x_i \in \{0, 1\}. \end{aligned}$$

- Greedy Solution

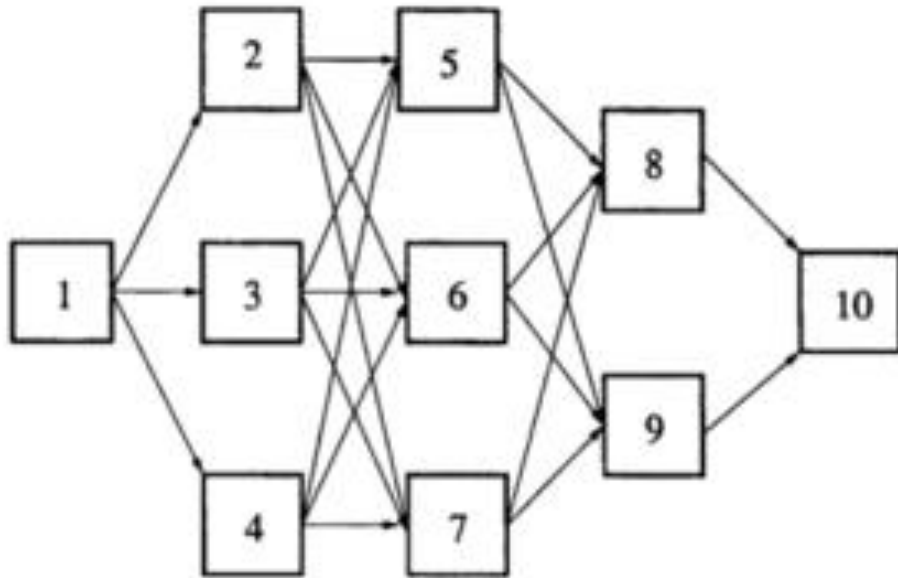
- Max value vs. Min weight vs. Max value/weight



- 0/1 Knapsack
- Fractional Knapsack

Stagecoach problem

Stagecoach problem (*TSP with less roads due to hostile territory*)



DP Solutions (cost 11):

1 -> 3 -> 5 -> 8 -> 10
1 -> 4 -> 5 -> 8 -> 10
1 -> 4 -> 6 -> 9 -> 10

	2	3	4		5	6	7
1	2	4	3				
				2	7	4	6
				3	3	2	4
				4	4	1	5

	8	9		10
5	1	4		
6	6	3		
7	3	3		

					10
				8	3
				9	4

Greedy Solution :

- 1 -> 2 (cost 2)
 - 2 -> 6 (cost 4)
 - 6 -> 9 (cost 3)
 - 9 -> 10 (cost 4)
- => **Cost 13 !!**

Dynamic Programming vs Greedy

- Both techniques are applied in optimization problems
- DP is applicable to problems in which the general optimum implies partial optima
- Greedy is applicable to problems for which the general optimum is obtained from partial (local) optima
- DP always provides the optimal solution
- Greedy does not guarantee finding the optimal solution

Example

- **Example:** take the problem of finding the optimal path between two vertices i and j of a graph
- The principle of optimality is verified
 - If the path from i to j is optimal and it passes through node x , then the path from i to x is optimal and also the path from x to j is optimal.
- The fact that the general optimum implies partial optima does not mean that partial optima also implies the general optimum
 - if the paths $i \rightarrow x$ and $x \rightarrow j$ are optimal, there is no guarantee that the path from i to j that passes through x is also optimal
- Greedy , DP

Recap today

- Problem solving methods
- Dynamic programming
- Greedy

Reading materials and useful links

1. The Python Programming Language - <https://www.python.org/>
2. The Python Standard Library - <https://docs.python.org/3/library/index.html>
3. The Python Tutorial - <https://docs.python.org/3/tutorial/>
4. M. Frentiu, H.F. Pop, Fundamentals of Programming, Cluj University Press, 2006.
5. MIT OpenCourseWare, Introduction to Computer Science and Programming in Python, <https://ocw.mit.edu>, 2016.
6. K. Beck, Test Driven Development: By Example. Addison-Wesley Longman, 2002. http://en.wikipedia.org/wiki/Test-driven_development
7. M. Fowler, Refactoring. Improving the Design of Existing Code, Addison-Wesley, 1999. <http://refactoring.com/catalog/index.html>