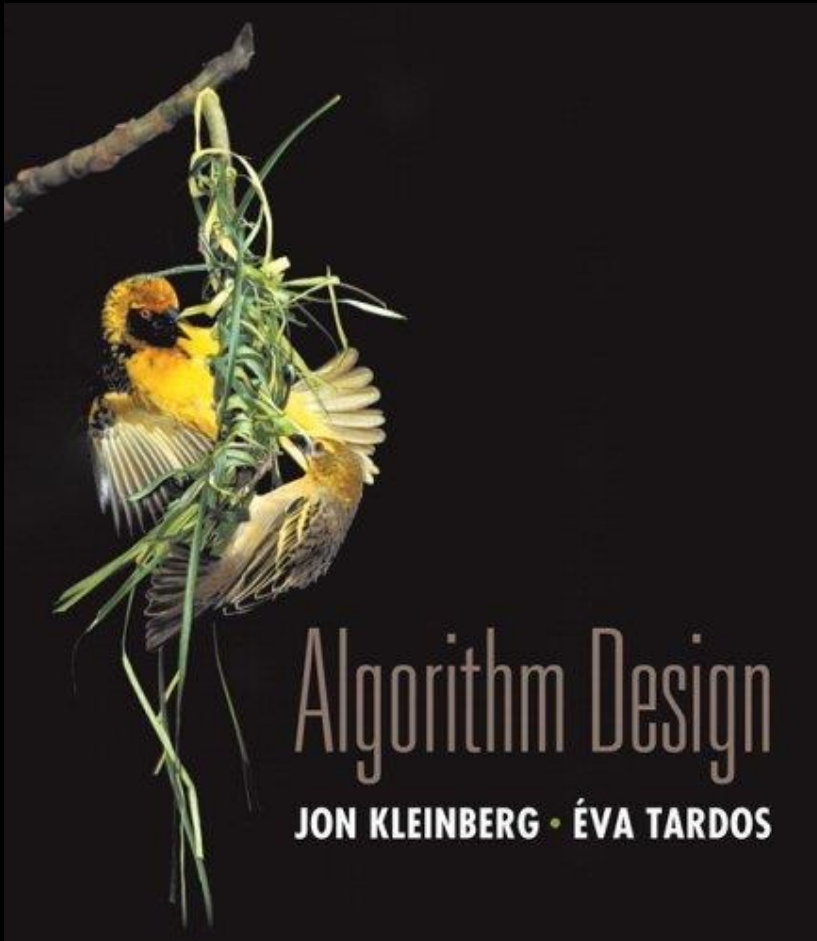


Chapter 6

Dynamic Programming



Slides by Kevin Wayne.
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Algorithmic Paradigms

Greed. Build up a solution incrementally, myopically optimizing some local criterion.

Divide-and-conquer. Break up a problem into two sub-problems, solve each sub-problem independently, and combine solution to sub-problems to form solution to original problem.

Dynamic programming. Break up a problem into a series of sub-problems with repetitions, and build up solutions to larger and larger sub-problems.

Optimal substructure

Dynamic Programming History

Bellman. Pioneered the systematic study of dynamic programming in the 1950s.

Etymology.

- Dynamic programming = planning over time.
- Secretary of Defense was hostile to mathematical research.
- Bellman sought an impressive name to avoid confrontation.
 - "it's impossible to use dynamic in a pejorative sense"
 - "something not even a Congressman could object to"

Reference: Bellman, R. E. *Eye of the Hurricane, An Autobiography*.

Dynamic Programming Applications

Areas.

- Bioinformatics.
- Control theory.
- Information theory.
- Operations research.
- Computer science: theory, graphics, AI, systems,

Some famous dynamic programming algorithms.

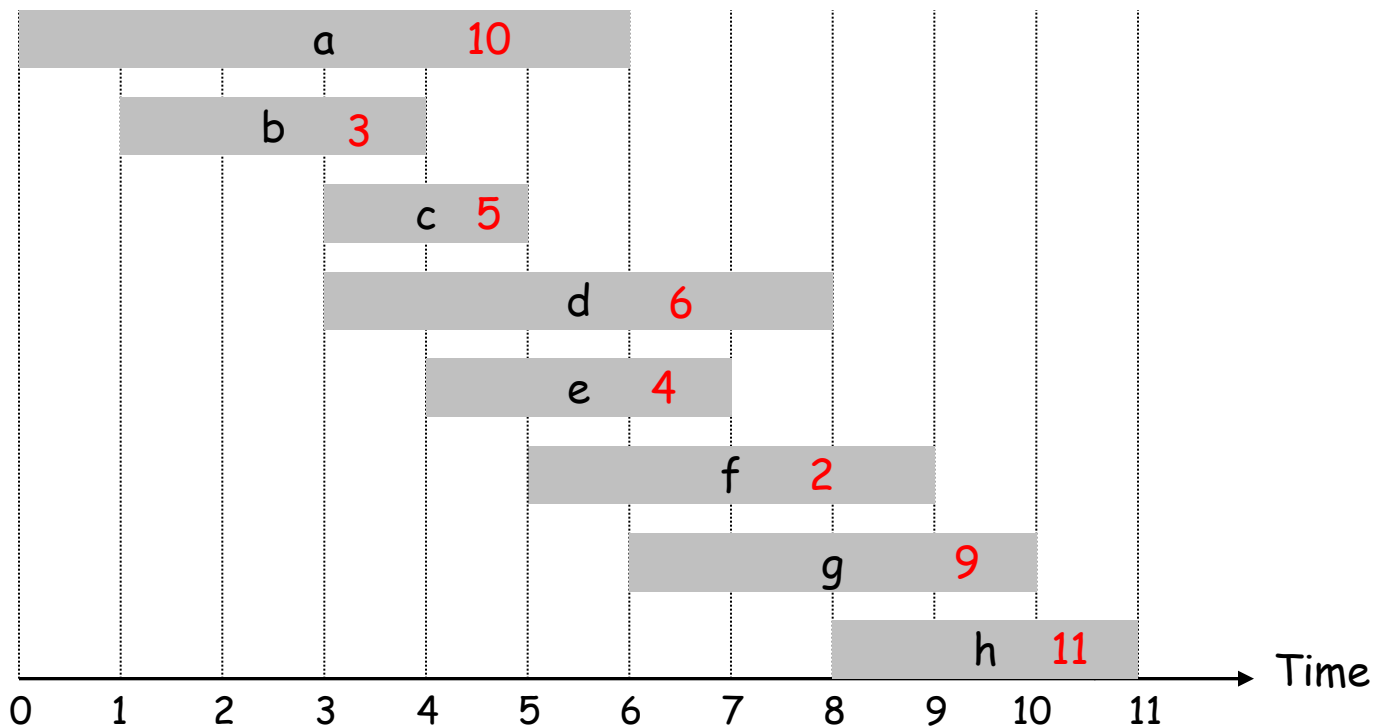
- Viterbi for hidden Markov models.
- Unix diff for comparing two files.
- DNA sequence comparison.
- Bellman-Ford for shortest path routing in networks.
- Cocke-Kasami-Younger for parsing context free grammars.

6.1 Weighted Interval Scheduling

Weighted Interval Scheduling

Weighted interval scheduling problem.

- Job j starts at s_j , finishes at f_j , and has value v_j .
- Two jobs compatible if they don't overlap.
- Goal: find maximum value subset of mutually compatible jobs.

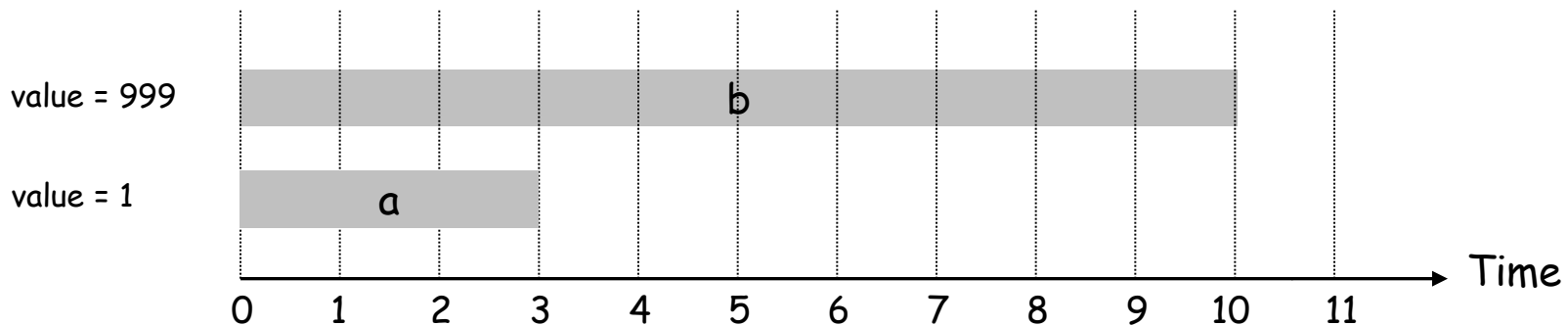


Unweighted Interval Scheduling Review

Recall. Greedy algorithm works if all values are 1.

- Consider jobs in ascending order of finish time.
- Add job to solution if it is compatible with previously chosen jobs.

Observation. Greedy algorithm can fail spectacularly if arbitrary values are allowed.

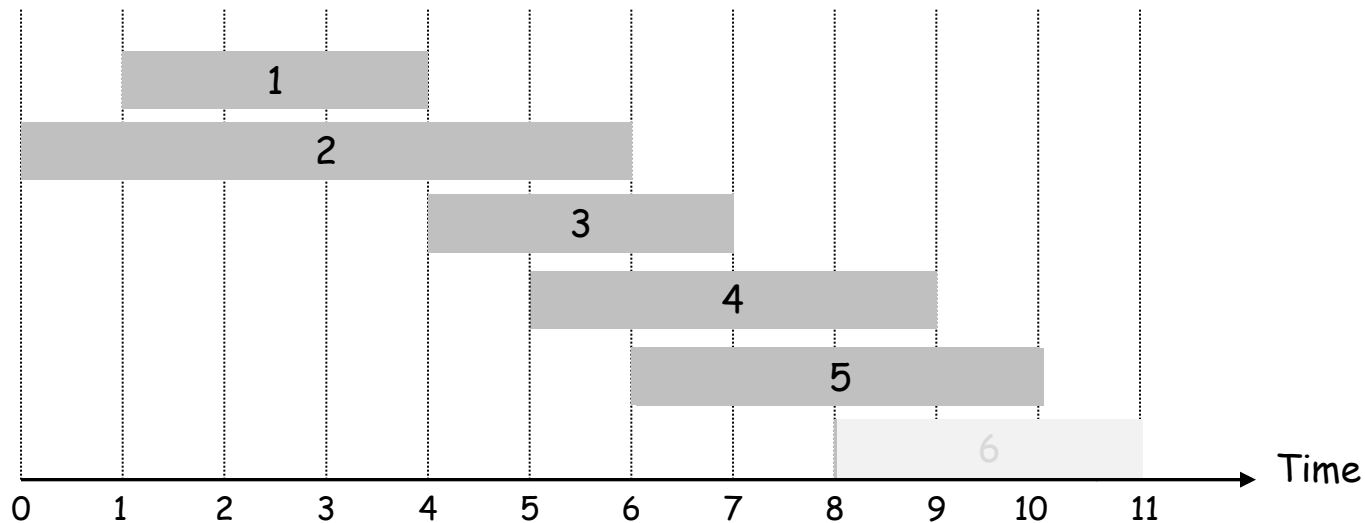


Weighted Interval Scheduling

Label jobs by finishing time: $f_1 \leq f_2 \leq \dots \leq f_n$.

Suppose we want to find optimal solution involving just jobs **1,2,...,5**

Need to decide whether to **include job 5** or to **not include job 5**



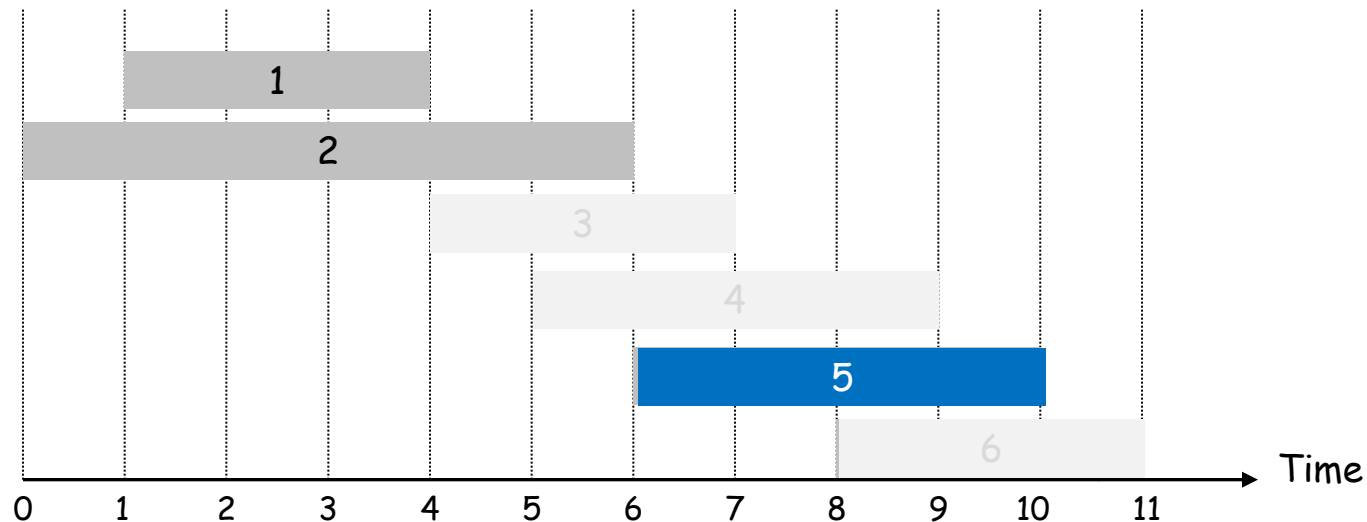
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Suppose we want to find optimal solution involving just jobs **1,2,...,5**

Need to decide whether to **include job 5** or to **not include job 5**

1. **If include** job 5 => also select optimally among jobs **1,2**



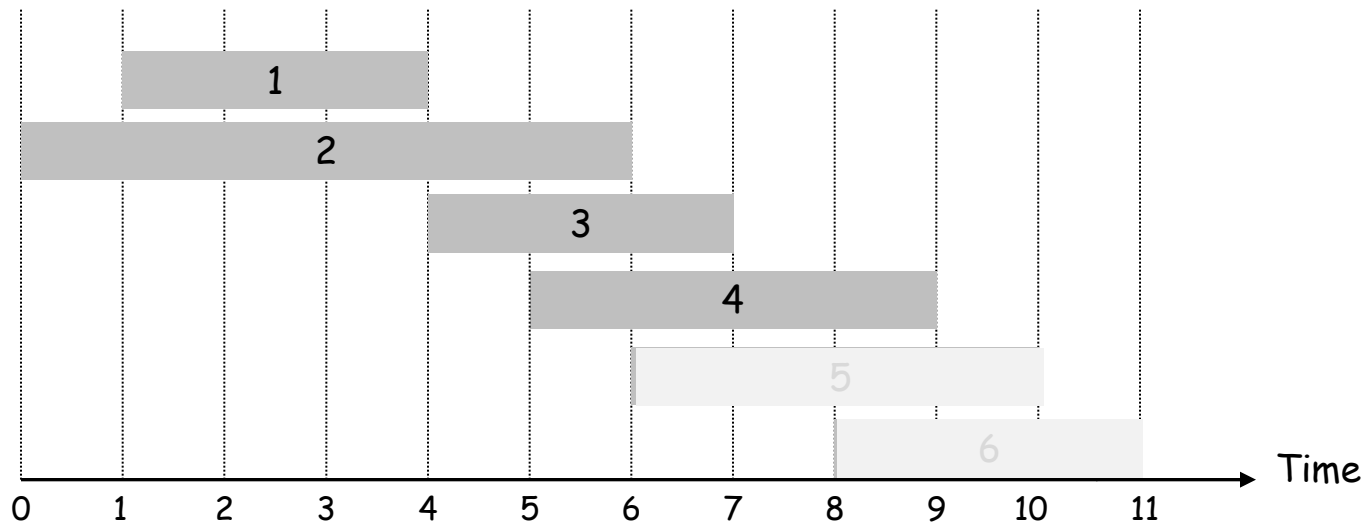
Weighted Interval Scheduling

Label jobs by finishing time: $f_1 \leq f_2 \leq \dots \leq f_n$.

Suppose we want to find optimal solution involving just jobs **1,2,...,5**

Need to decide whether to **include job 5** or to **not include job 5**

1. **If include** job 5 \Rightarrow also select optimally among jobs **1,2**
2. **If do not include** job 5 \Rightarrow select optimally among jobs **1,...,4**.

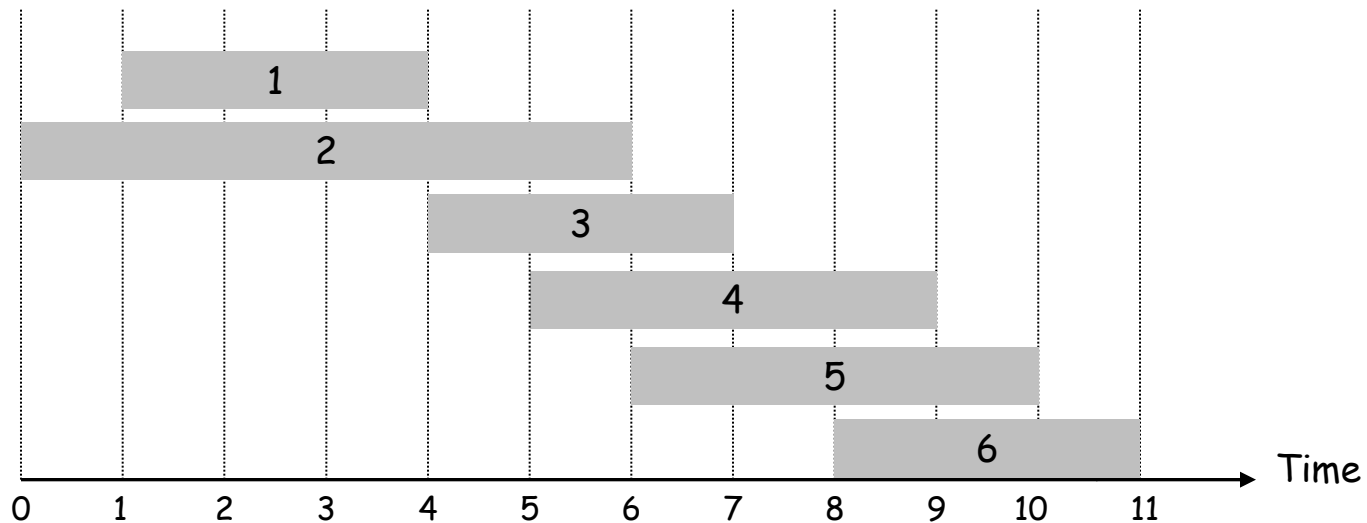


Weighted Interval Scheduling

More generally, define

$\text{lastCompat}(j) = \text{largest index } i < j \text{ such that job } i \text{ is compatible with } j.$

Ex: $\text{lastCompat}(5) = 2$, $\text{lastCompat}(4) = 1$, $\text{lastCompat}(1) = 0$



Weighted Interval Scheduling

More generally, define

$\text{lastCompat}(j)$ = largest index $i < j$ such that job i is compatible with j .

$\text{OPT}(j)$ = value of optimal solution to the problem consisting of jobs $1, 2, \dots, j$.

To compute $\text{OPT}(j)$ we have two options:

- Case 1: Solution **includes** job j .
 - can't use incompatible jobs $\{\text{lastCompat}(j) + 1, \dots, j - 1\}$
 - must include optimal solution to problem consisting of remaining compatible jobs **$1, 2, \dots, \text{lastCompat}(j)$** (=OPT(lastCompat(j)))
- Case 2: Solution does **not include** job j .
 - must include optimal solution to problem consisting of remaining compatible jobs **$1, 2, \dots, j-1$** (=OPT(j-1))

Pick the best option

$$\text{OPT}(j) = \begin{cases} 0 & \text{if } j = 0 \\ \max\{v_j + \text{OPT}(\text{lastCompat}(j)), \text{OPT}(j-1)\} & \text{otherwise} \end{cases}$$

Weighted Interval Scheduling

More generally, define

$\text{lastCompat}(j)$ = largest index $i < j$ such that job i is compatible with j .

$\text{OPT}(j)$ = value of optimal solution to the problem consisting of jobs $1, 2, \dots, j$.

Optimal substructure

To compute $\text{OPT}(j)$ we have

- Case 1: Solution **includes** job j .
 - can't use incompatible jobs $\{\text{lastCompat}(j) + 1, \dots, j - 1\}$
 - must include optimal solution to problem consisting of remaining compatible jobs $1, 2, \dots, \text{lastCompat}(j)$ ($=\text{OPT}(\text{lastCompat}(j))$)
- Case 2: Solution does **not include** job j .
 - must include optimal solution to problem consisting of remaining compatible jobs $1, 2, \dots, j-1$ ($=\text{OPT}(j-1)$)

Pick the best option

$$\text{OPT}(j) = \begin{cases} 0 & \text{if } j = 0 \\ \max\{v_j + \text{OPT}(\text{lastCompat}(j)), \text{OPT}(j-1)\} & \text{otherwise} \end{cases}$$

Weighted Interval Scheduling: Brute Force

$$OPT(j) = \begin{cases} 0 & \text{if } j = 0 \\ \max\{v_j + OPT(\text{lastCompat}(j)), OPT(j-1)\} & \text{otherwise} \end{cases}$$

We can use this expression to compute the optimal value $OPT(n)$

Brute force algorithm.

Input: $n, s_1, \dots, s_n, f_1, \dots, f_n, v_1, \dots, v_n$

Sort jobs by finish times so that $f_1 \leq f_2 \leq \dots \leq f_n$.

Compute $\text{lastCompat}(1), \text{lastCompat}(2), \dots, \text{lastCompat}(n)$

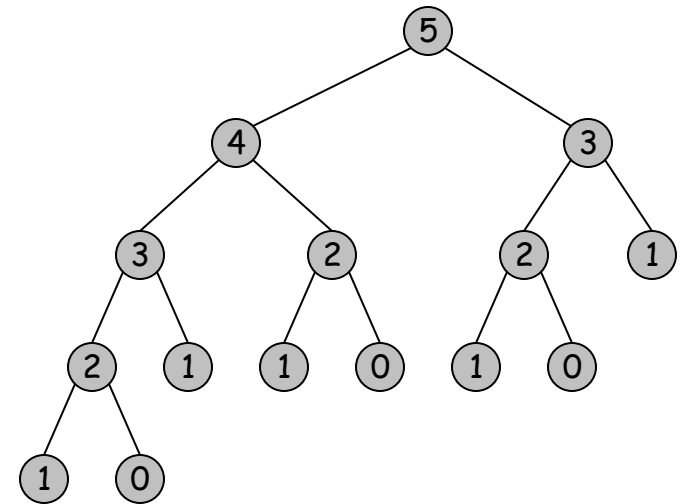
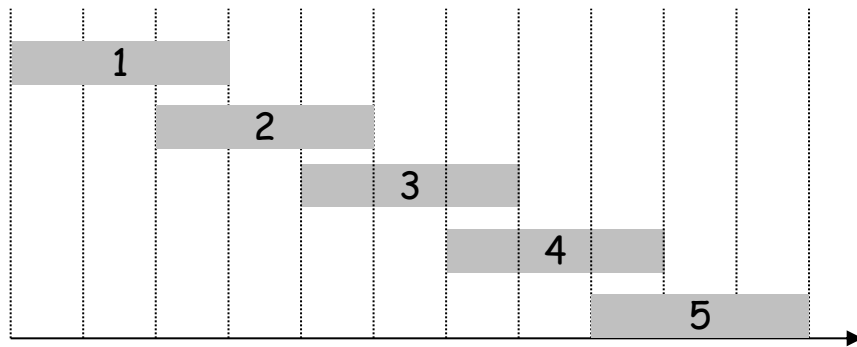
Return $\text{Compute-Opt}(n)$

```
Compute-Opt(j) {
    if (j = 0)
        return 0
    else
        return max(v_j + Compute-Opt(lastCompat(j)), Compute-Opt(j-1))
}
```

Weighted Interval Scheduling: Brute Force

Observation. This brute force algorithm has takes **exponential** time because of **redundant sub-problems**

Ex. Number of recursive calls for family of "layered" instances grows like Fibonacci sequence.



Q: Any ideas on how to decrease running time?

Weighted Interval Scheduling: DP I - Memoization

Dynamic Programming I - Memoization. Store results of each sub-problem in a cache; lookup as needed.

```
Input:  $n, s_1, \dots, s_n, f_1, \dots, f_n, v_1, \dots, v_n$ 
```

```
Sort jobs by finish times so that  $f_1 \leq f_2 \leq \dots \leq f_n$ .
```

```
Compute lastCompat(1), lastCompat(2), ..., lastCompat(n)
```

```
M[0] = 0 ← global array, want to have M[j]=OPT(j)
```

```
for j = 1 to n
```

```
    M[j] = empty
```

```
Run M-Compute-Opt(n)
```

```
-----
```

```
M-Compute-Opt(j) {
```

```
    if (M[j] is empty)
```

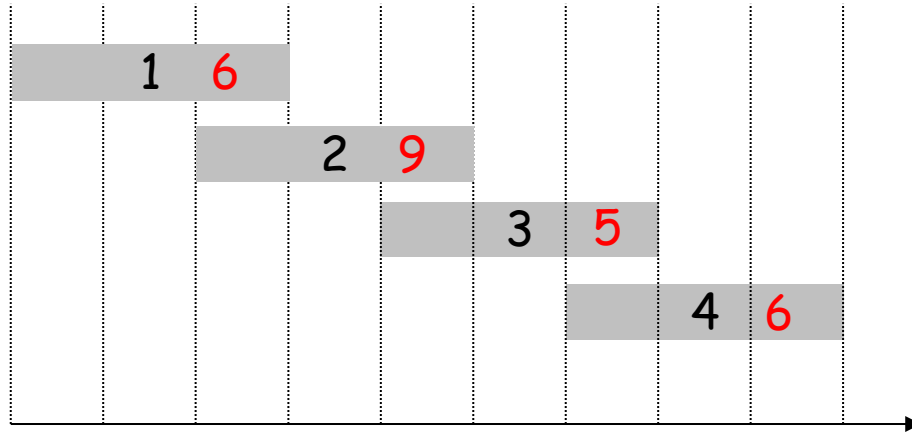
```
        M[j] = max( $w_j + \text{M-Compute-Opt}(\text{lastCompat}(j))$ ,  $\text{M-Compute-Opt}(j-1)$ )
```

```
    return M[j]
```

```
}
```


Weighted Interval Scheduling: DP 1 - Memoization

Ex: Run the **memoization** algorithm on the following instance



$M =$

| | | | | | |
|--|--|--|--|--|--|
| | | | | | |
|--|--|--|--|--|--|

Weighted Interval Scheduling: DP 1 - Memoization

- Analysis of running time: similar to DFS (we will ignore the time to sort and compute lastCompat to focus on main part)
- Running time = sum of costs of all calls $M\text{-Compute-Opt}(j)$, $j=0,\dots,n$
- Let us analyze $M\text{-Compute-Opt}(j)$ for a fixed j
 - The first time $M\text{-Compute-Opt}(j)$ is called, it makes two recursive calls
 - After the first time, it does not make any calls
 - So over the whole execution, $M\text{-Compute-Opt}(j)$ makes 2 calls
- Since $j=1,\dots,n$, the total number of calls is $O(n)$
- Each call takes constant time
- So the algorithm takes time $O(n)$.

Weighted Interval Scheduling: DP 2 - Bottom-Up

Dynamic Programming 2 - Bottom-up: Fill table M in **order** $M[0], M[1], \dots$

- When we try to fill $M[j]$ we already have all the information needed, namely $M[\text{lastCompat}(j)]$ and $M[j-1]$

```
Input:  $n, s_1, \dots, s_n, f_1, \dots, f_n, v_1, \dots, v_n$ 
```

```
Sort jobs by finish times so that  $f_1 \leq f_2 \leq \dots \leq f_n$ .
```

```
Compute  $\text{lastCompat}(1), \text{lastCompat}(2), \dots, \text{lastCompat}(n)$ 
```

```
Iterative-Compute-Opt {
```

```
     $M[0] = 0$ 
```

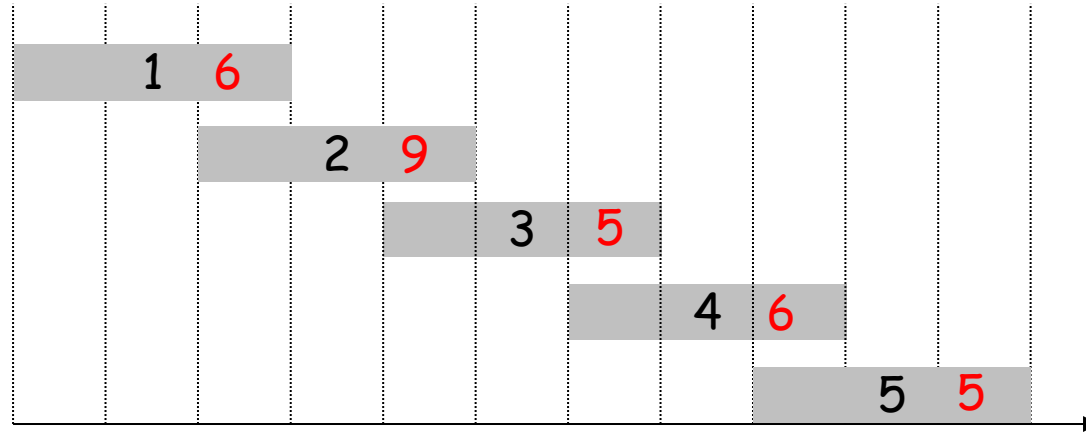
```
    for  $j = 1$  to  $n$ 
```

```
         $M[j] = \max(v_j + M[\text{lastCompat}(j)], M[j-1])$ 
```

```
}
```

Weighted Interval Scheduling: DP 2 - Bottom-Up

Ex: Run the **bottom-up** algorithm on the following instance

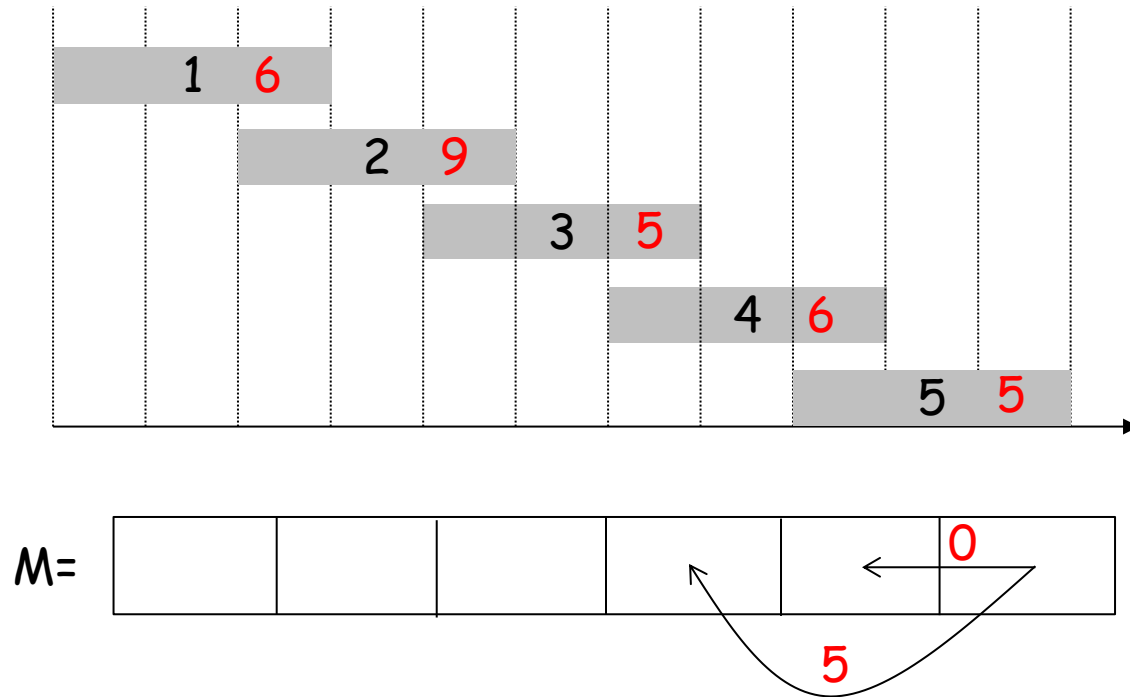


$M =$

| | | | | | |
|--|--|--|--|--|--|
| | | | | | |
|--|--|--|--|--|--|

Weighted Interval Scheduling: DP 3 - Shortest path

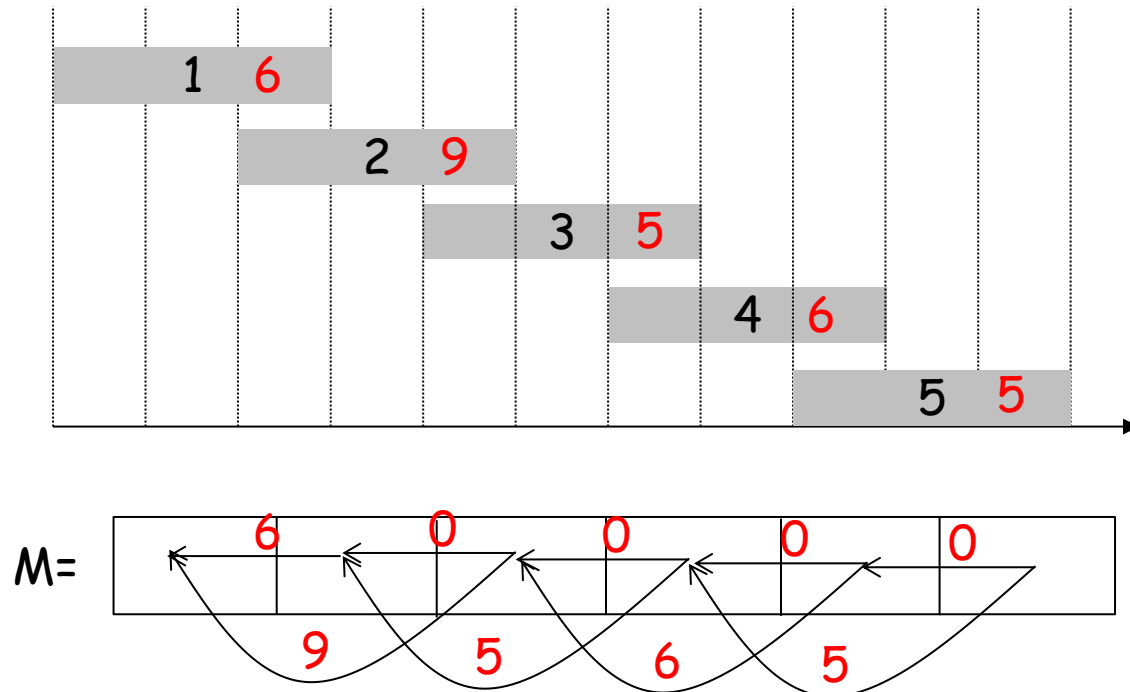
Remark: Every dynamic programming algorithm can also be seen as a shortest/longest path problem



$$OPT(j) = \begin{cases} 0 & \text{if } j = 0 \\ \max\{v_j + OPT(\text{lastCompat}(j)), OPT(j-1)\} & \text{otherwise} \end{cases}$$

Weighted Interval Scheduling: DP 3 - Shortest path

Remark: Every dynamic programming algorithm can also be seen as a shortest/longest path problem



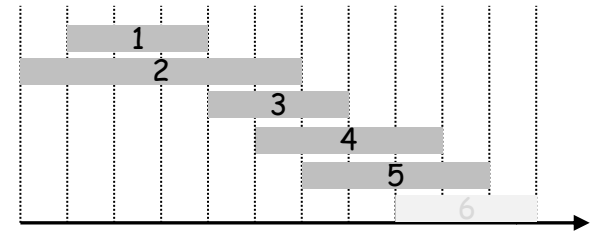
$$OPT(j) = \begin{cases} 0 & \text{if } j = 0 \\ \max\{v_j + OPT(\text{lastCompat}(j)), OPT(j-1)\} & \text{otherwise} \end{cases}$$

How does Dynamic Programming solution looks like?

1) Break problem into **sub-problems**

Sub-problem i : consider only tasks $1, \dots, i$

$OPT(i)$ = optimal value of sub-prob i
= best subset of tasks $1, \dots, i$



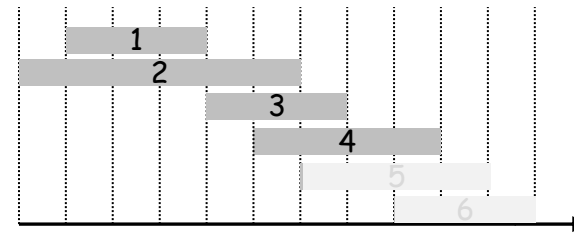
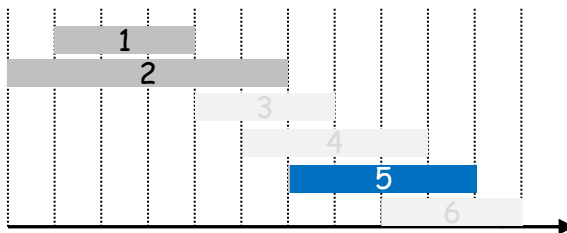
2) To solve sub-problem, **use smaller sub-problems**

Either:

include 5

does not

**Optimal
substructure**

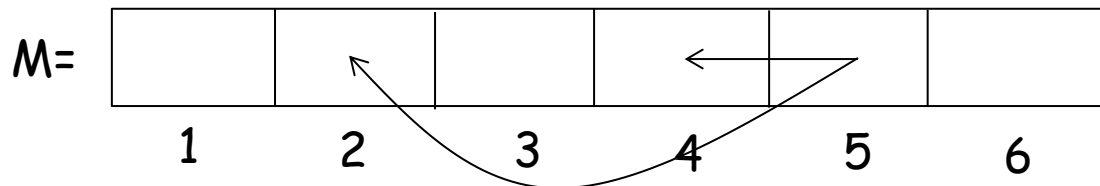


$$OPT(5) = \max\{ \text{val}(5) + OPT(2), \quad OPT(4) \}$$

How does Dynamic Programming solution looks like?

$$\text{OPT}(5) = \max\{ \text{val}(5) + \text{OPT}(2), \text{OPT}(4) \}$$

- 3) Create **table to store optimal** value of each sub-problem.
Fill up table in **starting from smallest** sub-problems
(so always have information needed)



Maior subsequência crescente

Maior subsequência crescente

Entrada:

$A = (a(1), a(2), \dots, a(n))$ uma sequência de números reais distintos.

Objetivo:

Encontrar a maior subsequência **crescente** de A

Exemplo

- $A = (2, 3, 14, 5, 9, 8, 4)$
- $(2, 3, 8)$ e $(3, 5, 9)$ são subsequências crescentes de tamanho 3
- As maiores subsequências crescentes de A são $2, 3, 5, 9$ e $2, 3, 5, 8$

Maior subsequência crescente

Q: Sub-problemas?

- Seja $L(j)$: tamanho da maior subsequência crescente que **termina em $a(j)$** ($a(j)$ **pertence** a subsequência)
- Exemplo $A = (2, 3, 14, 5, 9, 8, 4)$
- $L(1)=1, L(2)=2, L(3)=3, L(4)=3, L(5)=4, L(6)=4, L(7)=3$
- O tamanho da maior subsequência crescente é

$$\max \{ L(1), L(2), \dots, L(n) \}$$

- Temos a seguinte equação para $L(j)$:
[Tente para $L(6)$ com $A = (2, 3, 14, 5, 9, 8, 4)$]

$$L(j) = \max_i \{ 1+L(i) \mid i < j \text{ e } a(i) < a(j) \}, \text{ para } j > 1$$
$$L(1) = 1$$

Maior subsequência crescente

Q: Sub-problemas?

- Seja $L(j)$: tamanho da maior subsequência crescente que **termina em $a(j)$** ($a(j)$ **pertence** a subsequência)
- Exemplo $A = (2, 3, 14, 5, 9, 8, 4)$
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$$L(j) = \max\{1, \max_i \{ 1+L(i) \mid i < j \text{ e } a(i) < a(j) \}, \text{ para } j > 1 \}$$
$$L(1) = 1$$

Maior subsequência crescente: encontrando o tamanho

```
Input:  $n, a_1, \dots, a_n,$   
  
 $L(1) \leftarrow 1, \text{pre}(1) \leftarrow 0$   
For  $j=2$  to  $n$   
   $L(j) \leftarrow 1, \text{pre}(j) \leftarrow 0$   
  For  $i=1$  to  $j-1$  // faz  $L(i) \leftarrow \max_i \{ 1+L(i) \mid i < j \text{ e } a(j) > a(i) \}$   
    If  $A(i) < A(j)$  and  $1+L(i) > L(j)$  then  
       $L(j) \leftarrow 1+L(i)$   
       $\text{pre}(j) \leftarrow i$  // atualiza predecessor  
    End If  
  End For  
End For  
  
 $MSC \leftarrow 0$   
For  $i=1$  to  $n$  // encontra maior L  
   $MSC \leftarrow \max\{ MSC, L(i) \}$   
End For
```

[Fazer traço pra exemplo $A = (4, 2, 3, 5)$ com $\text{pre}(\cdot)$]

- $\text{pre}(j)$: é utilizado para guardar o predecessor de j na maior subsequência crescente
- Complexidade $O(n^2)$

Encontrando a subsequencia (recursivamente)

Q: Algoritmo anterior calcula **tamanho** da maior subsequencia crescente.
Como encontrar a **subsequencia em si**?

A: 1) Encontra $L(j)$ com maior valor
2) Adiciona j a soluçã, segue $pre(j)$, adicionando, etc.

```
Input: n, L(1), ..., L(n), pre(1), ..., pre(n), OPT
```

```
j ← 0
```

```
While L(j) <> OPT //encontra L(j) com maior valor
```

```
  j++
```

```
End While
```

```
Find_Subsequence(j)
```

```
Proc Find_Subsequence(j)
```

```
  If j=0
```

```
    Return
```

```
  else
```

```
    Add j to the solution;
```

```
    Find_Subsequence(pre(j))
```

```
  End if
```

```
Return
```

Complexidade $O(n)$

Maior subsequência crescente

Exercício: Escreva a versão da programação dinâmica com memoização para resolver esse problema de maior subsequencia crescente

Exercise: Placing billboards

Placing billboards

Exercise: You need to decide where to put multiple advertisement on a highway of M kms.

- There are n possible places where you can place an advertisement given by x_1, x_2, \dots, x_n in $[0, M]$.
- Placing an advertisement at x_i gives value r_i .
- You cannot put two advertisements at distance ≤ 5 kms from each other.
- **Goal:** Find best set of places to put advertisement.

Ex: $M=20$, $\{x_1, x_2, x_3, x_4\} = \{6, 7, 12, 14\}$, and $\{r_1, r_2, r_3, r_4\} = \{5, 6, 5, 1\}$.

One optimal solution is to put advertisement at x_1 and x_3

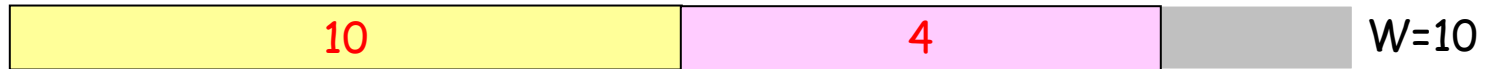
Solve this problem using dynamic programming

6.4 Knapsack Problem

Knapsack Problem

Knapsack problem.

- Given n objects and a backpack of **size W**
- Item i has **size $w_i > 0$** and has **value $v_i > 0$** .
- Sizes are **integers**.
- **Goal:** pick set of items that fit in the backpack and maximize total value.



Ex: { 3, 4 } has value 40.

W = 11

| Item | Value | Size |
|------|-------|------|
| 1 | 1 | 1 |
| 2 | 6 | 2 |
| 3 | 18 | 5 |
| 4 | 22 | 6 |
| 5 | 28 | 7 |

Knapsack Problem: Greedy Attempt

Greedy: repeatedly add item with maximum ratio v_i / w_i .

Ex: { 5, 2, 1 } achieves only value = 35 \Rightarrow greedy not optimal

.

| W = 11 | Item | Value | Size |
|--------|------|-------|------|
| | 1 | 1 | 1 |
| | 2 | 6 | 2 |
| | 3 | 18 | 5 |
| | 4 | 22 | 6 |
| | 5 | 28 | 7 |

Dynamic Programming: False Start

Q: Sub-problems?

Def. $OPT(i) = \max$ profit subset of items $1, \dots, i$.

- Case 1: OPT does not select item i .
 - OPT selects best of $\{ 1, 2, \dots, i-1 \}$
- Case 2: OPT selects item i .
 - accepting item i does not immediately imply that we will have to reject other items
 - without knowing which other items were selected before i , we don't even know if we have enough room for i

Conclusion. Need more sub-problems!

Dynamic Programming: Adding a New Variable

Def. $OPT(i, w)$ = max profit subset of items 1, ..., i with occupation limit w.

Q: What is a recursive expression for $OPT(i, w)$?

- Case 1: OPT does not select item i .
 - OPT selects best of $\{ 1, 2, \dots, i-1 \}$ using size limit w
- Case 2: OPT selects item i .
 - new size limit = $w - w_i$
 - OPT selects best of $\{ 1, 2, \dots, i-1 \}$ using this new size limit

$$OPT(i, w) = \begin{cases} 0 & \text{if } i = 0 \\ OPT(i-1, w) & \text{if } w_i > w \\ \max \{ OPT(i-1, w), v_i + OPT(i-1, w - w_i) \} & \text{otherwise} \end{cases}$$

Knapsack Problem: Bottom-Up

Dynamic programming. Fill up an n -by- W array to compute $OPT(i,w)$

Q: In which order should we fill this array?

A: Start with $OPT(0, 0)$, then $OPT(0, 1)$, $OPT(0, 2)$...; then $OPT(1,0)$, $OPT(1,2)$,...

```
Input:  $n, w_1, \dots, w_N, v_1, \dots, v_N$ 

for  $w = 0$  to  $W$ 
     $M[0, w] = 0$ 

for  $i = 1$  to  $n$ 
    for  $w = 1$  to  $W$ 
        if  $(w_i > w)$ 
             $M[i, w] = M[i-1, w]$ 
        else
             $M[i, w] = \max \{M[i-1, w], v_i + M[i-1, w-w_i]\}$ 

return  $M[n, W]$ 
```

Knapsack Algorithm

←————— W + 1 —————→

| | | | | | | | | | | | | | |
|---------|-------------------|---|---|---|---|---|----|----|----|----|----|----|----|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| $n + 1$ | ϕ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | { 1 } | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | { 1, 2 } | 0 | 1 | 6 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| | { 1, 2, 3 } | 0 | 1 | 6 | 7 | 7 | 18 | 19 | 24 | 25 | 25 | 25 | 25 |
| | { 1, 2, 3, 4 } | 0 | 1 | 6 | 7 | 7 | 18 | 22 | 24 | 28 | 29 | 29 | 40 |
| | { 1, 2, 3, 4, 5 } | 0 | 1 | 6 | 7 | 7 | 18 | 22 | 28 | 29 | 34 | 34 | 40 |

OPT: { 4, 3 }
 value = 22 + 18 = 40

W = 11

| Item | Value | Weight |
|------|-------|--------|
| 1 | 1 | 1 |
| 2 | 6 | 2 |
| 3 | 18 | 5 |
| 4 | 22 | 6 |
| 5 | 28 | 7 |

Knapsack Problem: Running Time

Running time. $\Theta(n W)$.

- **Not polynomial** in input size! The input size is $(\log W + n)$
- "Pseudo-polynomial."
- Decision version of Knapsack is NP-complete. [Chapter 8]

Knapsack approximation algorithm. There exists a polynomial algorithm that produces a feasible solution that has value within 0.01% of optimum. [Section 11.8]

Knapsack Problem

Exercise: Write down a pseudo-code to give what are the items in the optimal solution (the previous algorithm only gives the value of the optimal solution)

Exercise: A moving consulting company

A moving consulting company

Exercise: You have a small consulting company. Your clients are mostly in Rio and Sao Paulo.

- In each month it can run its business either from a Rio office or Sao Paulo office.
- In month i you have **cost R_i** if run from Rio, and **S_i** if run from Sao Paulo
- If you run the business from one city at month i and another at month $i+1$, then you need to spend a fixed cost **M** for moving costs.
- **Goal:** Given n months, decide where your office should be in every month to minimize total cost

Ex: $M = 10$, $\{R_1, R_2, R_3, R_4\} = \{1, 3, 20, 30\}$, $\{S_1, S_2, S_3, S_4\} = \{50, 20, 2, 4\}$

Optimal solution is [Rio, Rio, SP, SP], with cost $1+3+2+4+10=20$

1. Show that the strategy of running the office from the city with smallest costs in each month does not minimize the total cost
2. Solve this problem using dynamic programming [Find actual solution]

6.6 Edit Distance

Edit Distance

How similar are two strings?

- **ocurrance**
- **occurrence**

Idea: Count **minimum** number of **operations** needed to transform one string into the other

- Insertion
- Deletion
- Character substitution

o c u r r a n c e -

o c c u r r e n c e

6 substitutions, 1 deletion

o c - u r r a n c e

o c c u r r e n c e

1 deletion, 1 substitution

o c - u r r - a n c e

o c c u r r e - n c e

2 deletions, 1 insertion

Edit Distance

Problem: Given two strings $x=x_1,\dots,x_n$ and $y=y_1,\dots,y_m$ compute the **minimum** number of operations to transform x into y

x = o c u r r a n c e

y = o c c u r r e n c e

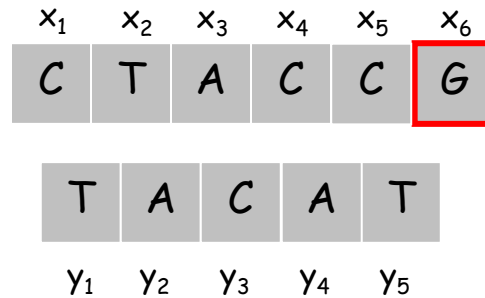
Applications.

- Basis for Unix diff
- Auto correction, spell checking
- Computational biology

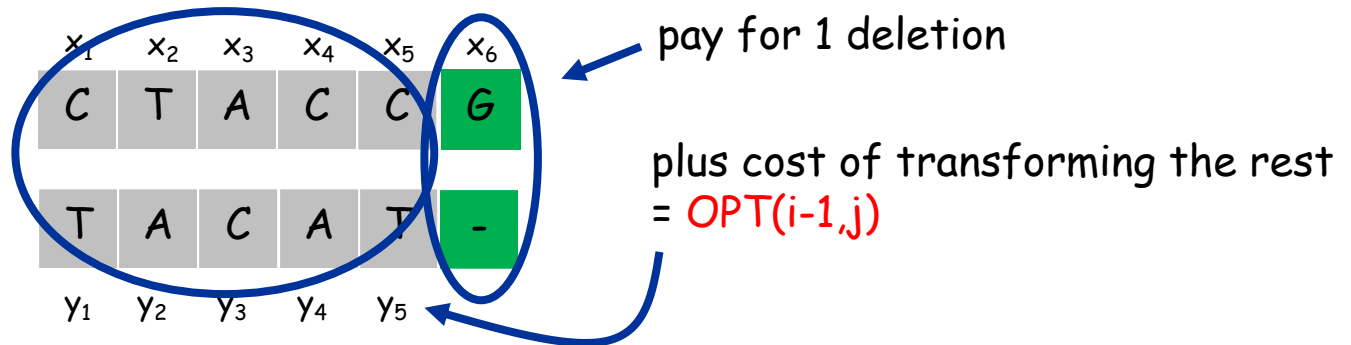
Edit Distance: Optimal substructure

Subproblems: $OPT(i, j) = \min$ cost of transforming $x_1 x_2 \dots x_i$ into $y_1 y_2 \dots y_j$.

Recursive relationship: Think of decision of which operation to apply to the end of the first string

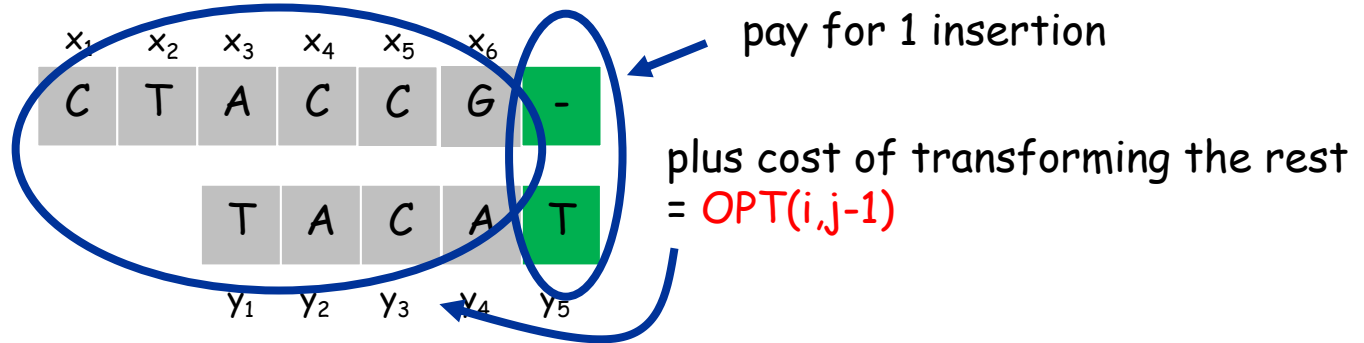


Option 1: Delete letter x_i

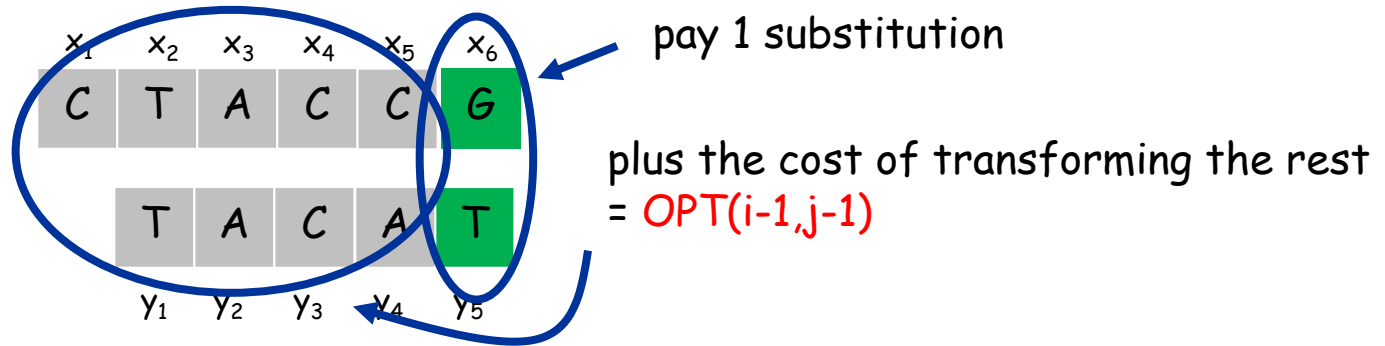


Edit Distance: Optimal substructure

Option 2: Insert letter y_j after x_i

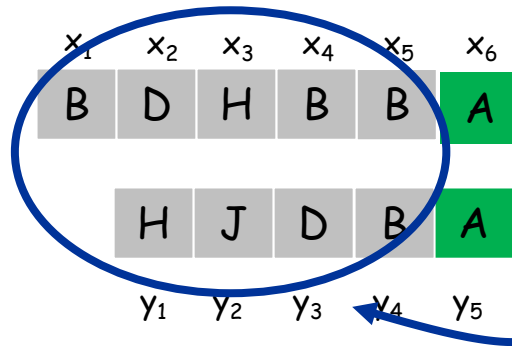


Option 3: If $x_i \neq y_j$, substitute x_i for y_j



Edit Distance: Optimal substructure

Option 4: If $x_i = y_j$, just "match" x_i and y_j



just pay the cost of transforming the rest
= $OPT(i-1, j-1)$

Edit Distance: Optimal substructure

So we have the following recursive relationship:

If $x_i \neq y_j$

$$\text{OPT}(i,j) = \min\{ 1 + \text{OPT}(i-1,j), 1 + \text{OPT}(i,j-1), 1 + \text{OPT}(i-1,j-1) \}$$

Else ($x_i = y_j$)

$$\text{OPT}(i,j) = \min\{ 1 + \text{OPT}(i-1,j), 1 + \text{OPT}(i,j-1), \text{OPT}(i-1,j-1) \}$$

With boundary cases

$$\text{OPT}(i,0) = i \quad \text{for all } i$$

$$\text{OPT}(0,j) = j \quad \text{for all } j$$

Notice $\text{OPT}(m,n)$ gives the edit distance between the whole strings

Edit Distance: Algorithm

```
EditDistance( $x_1x_2\dots x_m$ ,  $y_1y_2\dots y_n$ ) {  
  for i = 0 to m  
    M[i, 0] = i  
  for j = 0 to n  
    M[0, j] = j  
  
  for i = 1 to m  
    for j = 1 to n  
      if  $x_i \neq y_j$   
        M[i, j] = min(1 + M[i-1, j], 1 + M[i, j-1], 1 + M[i-1, j-1])  
      else  
        M[i, j] = min(1 + M[i-1, j], 1 + M[i, j-1], M[i-1, j-1])  
  
  return M[m, n]  
}
```

Analysis. $\Theta(mn)$ time