Dynamic Programming

DP technique

Guideline

W activity selection

0-1 Knapsack

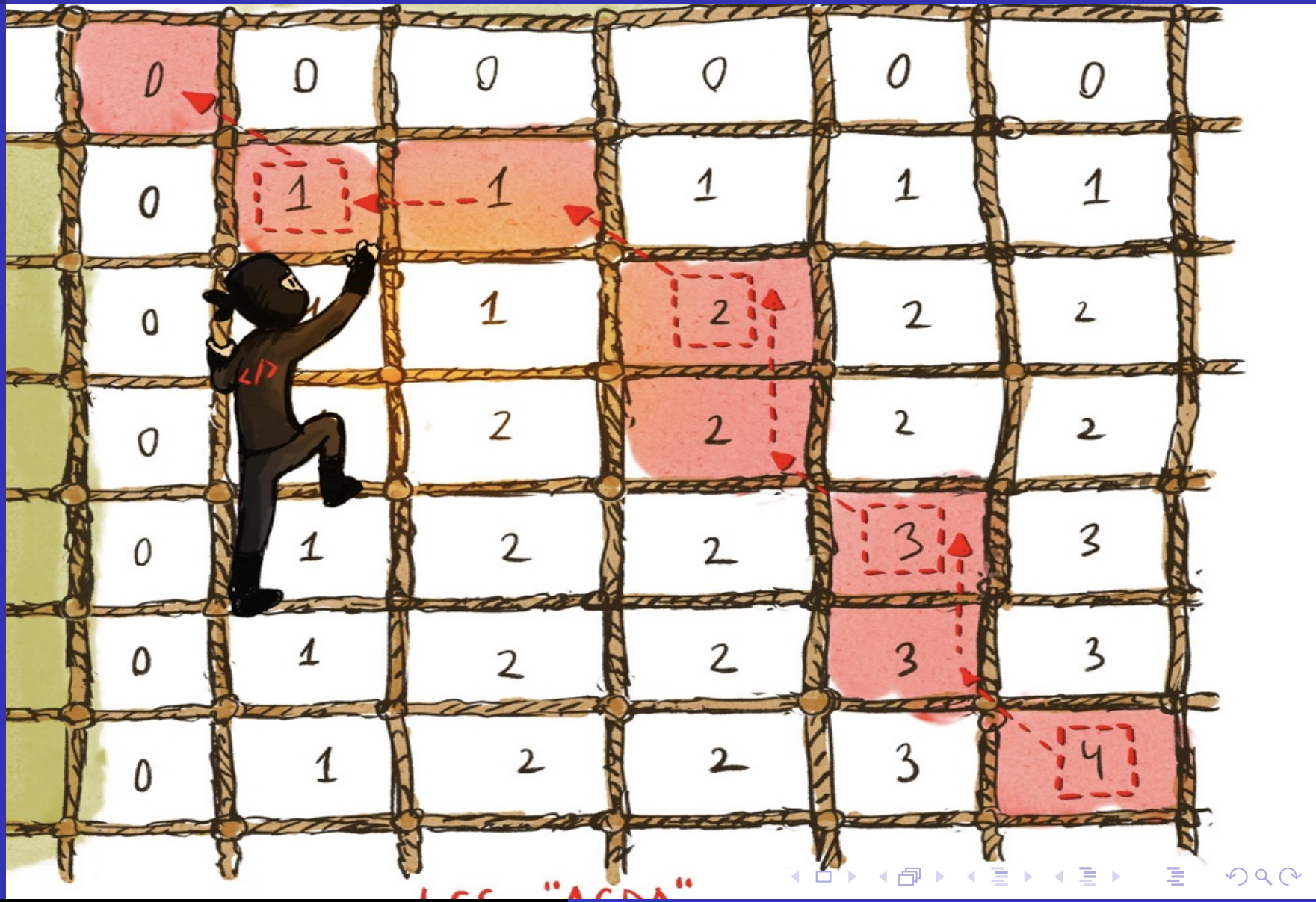
DP for pairing sequences

Framework

Edit distance

Longest common subsequence (LCS)

Longest common substring



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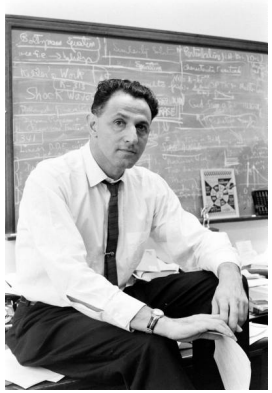
For a gentle introduction to DP see Chapter 6 in DPV, KT and CLRS also have a chapter devoted to DP.

Richard Bellman: *An introduction to the theory of dynamic programming* RAND, 1953



Dynamic programming is a powerful technique for efficiently implement *recursive algorithms* by storing partial results and re-using them when needed.

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Dynamic Programming works efficiently when:

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Dynamic Programming works efficiently when:

- Subproblems: There must be a way of breaking the global optimization problem into subproblems, each having a similar structure to the original problem but smaller size.

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Dynamic Programming works efficiently when:

- Subproblems: There must be a way of breaking the global optimization problem into subproblems, each having a similar structure to the original problem but smaller size.
- Optimal sub-structure: An optimal solution to a problem must be a composition of optimal subproblem solutions, using a relatively simple combining operation.

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Dynamic Programming works efficiently when:

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- Repeated subproblems: The recursive algorithm solves a small number of distinct subproblems, but they are repeatedly solved many times.

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- Repeated subproblems: The recursive algorithm solves a small number of distinct subproblems, but they are repeatedly solved many times.

This last property allows us to take advantage of memoization, store intermediate values, using the appropriate dictionary data structure, and reuse when needed.

Difference with greedy

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- Greedy problems have the greedy choice property: locally optimal choices lead to globally optimal solution. We solve recursively one subproblem

Difference with greedy

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- Greedy problems have the greedy choice property: locally optimal choices lead to globally optimal solution. We solve recursively one subproblem
- I.e. In DP we solve all possible subproblems, while in greedy we are bound for the initial choice

Difference with divide and conquer

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- Both require recursive programming with subproblems with a similar structure to the original

Difference with divide and conquer

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- Both require recursive programming with subproblems with a similar structure to the original
- D & C breaks a problems into a small number of subproblems each of them with size a fraction of the original size (size/b).

Difference with divide and conquer

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- Both require recursive programming with subproblems with a similar structure to the original
- D & C breaks a problems into a small number of subproblems each of them with size a fraction of the original size (size/b).
- In DP, we break into many subproblems with smaller size, but often, their sizes are not a fraction of the initial size.

Guideline to implement Dynamic Programming

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1. *Characterize the structure of subproblems:* make sure space of subproblems is not exponential. Define variables.
2. Define recursively the value of an optimal solution: Find the correct recurrence, with solution to larger problem as a function of solutions of sub-problems.
3. *Compute, memoization/bottom-up, the cost of a solution:* using the recursive formula, tabulate solutions to smaller problems, until arriving to the value for the whole problem.
4. *Construct an optimal solution:* compute additional information to trace-back an optimal solution from optimal value.

Weighted Activity Selection problem

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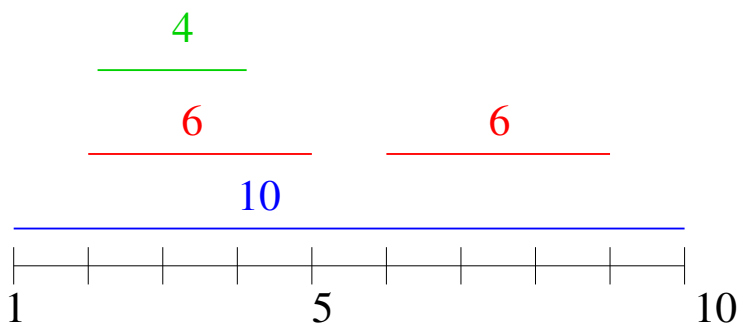
Weighted Activity Selection problem: Given a set $S = \{1, 2, \ldots, n\}$ of activities to be processed by a single resource. Each activity i has a start time s_i and a finish time f_i, with $f_i > s_i$, and a weight w_i. Find the set of mutually compatible activities such that it maximizes $\sum_{i \in S} w_i$

Recall: We saw that some greedy strategies did not provide always a solution to this problem.



W Activity Selection: a recursive solution for the cost

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- Let us think of a backtracking algorithm for the problem.
- The solution is the maximum cost of a correct selection of activities.
- We can adapt the backtracking algorithm to compute all subsets.

W Activity Selection: a recursive solution for the cost

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- When processing element i, we branch
  - add i to the solution S, then all activities that overlap with i cannot be in S.
  - i is not in the solution.

W Activity Selection: a recursive solution for the cost

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- When processing element i, we branch
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- For the unweighted case, the greedy algorithm sorts activities are by finish time.

W Activity Selection: a recursive solution for the cost

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  - i is not in the solution.
- For the unweighted case, the greedy algorithm sorts activities are by finish time. Assuming $f_1 \leq f_2 \leq \cdots \leq f_n$.
  - An incompatibility with a task j with $f_j \geq t_i$ will be discovered when dealing with task j.
  - Activity i is not compatible with activity $j < i$ when $f_j \geq s_i$.
  - Activity i can be incompatible with a contiguous set of activities $i-1, i-2, \ldots$.

W Activity Selection cost: recursive solution

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WAS-1 (i)
if $i == 1$ **then**
  return (w_1)
if $i == 0$ **then**
  return (0)
Let j be the largest integer $j < i$ such that $f_j \leq s_i$, 0 if none is compatible.
return $(\max\{\textbf{WAS-1}(j) + w_i, \textbf{WAS-1}(i-1)\})$

Each backtracking call receives the weight of a partial solution from and returns the weight of the best solution considering i.

W Activity Selection cost: recursive solution

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W Activity Selection cost: recursive solution

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How many subproblems appear here?

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How many subproblems appear here? $O(n)$!.

DP from WAS-1: a recurrence

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- We have n activities with $f_1 \leq f_2 \leq \cdots \leq f_n$ and weights w_i, $1 \leq i \leq n$.

DP from WAS-1: a recurrence

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- We have n activities with $f_1 \leq f_2 \leq \cdots \leq f_n$ and weights w_i, $1 \leq i \leq n$.
- Supproblems calls WAS-1(i), $0 \leq i \leq n$
  - WAS[i]: Maximize the weight of the activity selection for activities $\{1, \ldots, i\}$, for $0 \leq i \leq n$.
  - A recursive call returns this maximum.
  - There are only $O(n)$ subproblems!

DP from WAS-1: a recurrence

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  - WAS[i]: Maximize the weight of the activity selection for activities $\{1, \ldots, i\}$, for $0 \leq i \leq n$.
  - A recursive call returns this maximum.
  - There are only $O(n)$ subproblems!
- Let Opt(i) be the weight of an optimal solution O_i to the subproblem WAS[i].

DP from WAS-1: a recurrence

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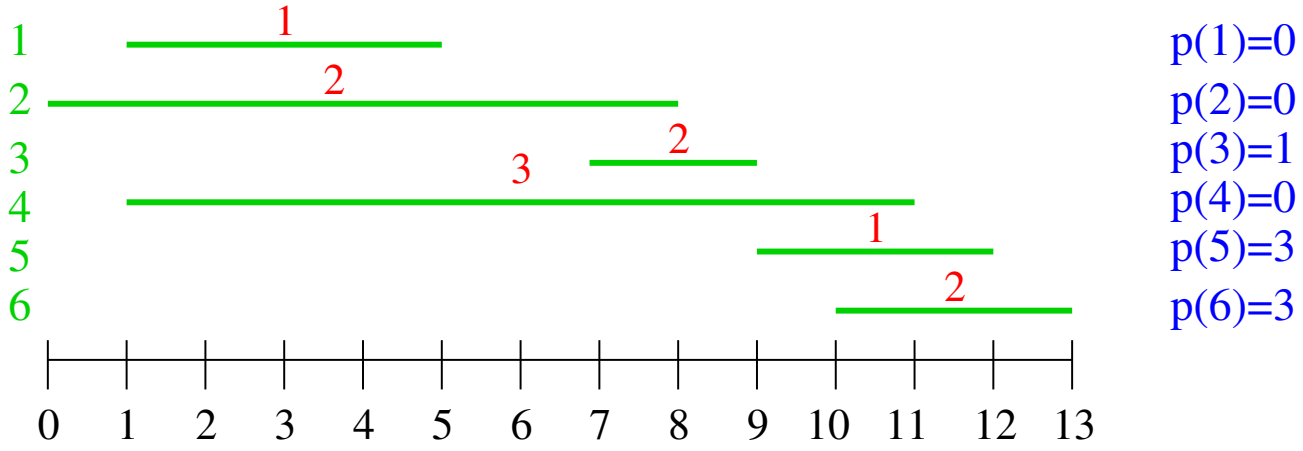
Define $p(i)$ to be the largest integer $j < i$ such that i and j are disjoints ($p(i) = 0$ if no disjoint $j < i$ exists).



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Reinterpreting WAS-1 botton-up, using $p(i)$, we get

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Reinterpreting WAS-1 botton-up, using $p(i)$, we get

$$\mathrm{Opt}(j) = \begin{cases} 0 & \text{if } j = 0 \\ \max\{(\mathrm{Opt}(p[j]) + w_j), \mathrm{Opt}[j-1]\} & \text{if } j \geq 1 \end{cases}$$

We add activity 0 for compatibility with p.

DP from WAS-2: a recurrence

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$$\mathrm{Opt}(j) = \begin{cases} 0 & \text{if } j = 0 \\ \max\{(\mathrm{Opt}(p[j]) + w_j), \mathrm{Opt}[j-1]\} & \text{if } j \geq 1 \end{cases}$$

Correctness: The base case is correct. From the previous discussion, we have two cases:

1.- $j \in O_j$:

- As j is part of the solution, no jobs $\{p(j)+1, \ldots, j-1\}$ are in O_j,
- $O_j - \{j\}$ must be an optimal solution for $\{1, \ldots, p[j])\}$, otherwise then $O'_j = O_{p[j]} \cup \{j\}$ will be better (optimal substructure)

2.- If $j \notin O_j$: then O_j is an optimal solution to $\{1, \ldots, j-1)\}$.

DP from WAS-1: Computing p values

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- We need to compute efficiently $p(i)$
  - sort the activities by increasing values of start time.
  - merge the sorted list of finishing times an the sorted list of start times, in case of tie put before the finish times.
  - $p[j]$ is the last activity whose finish time precedes s_j in the combined order, activity 0, if no finish time precedes s_j
- We can thus compute the p values in $O(n \lg n + n) = O(n \lg n)$ time.

DP from WAS-1: omputing p values

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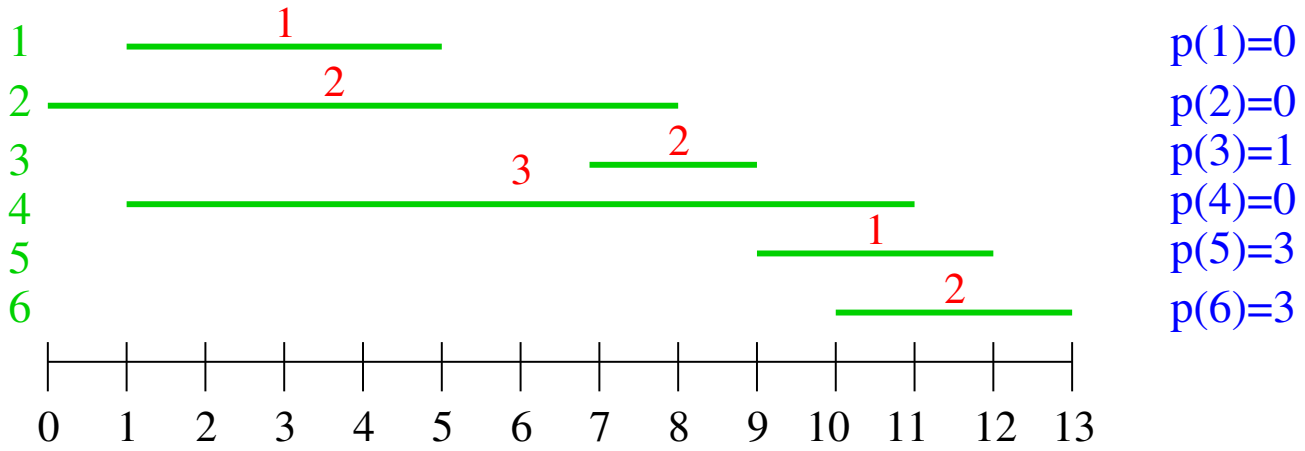

Sorted finish times: 1:5, 2:8, 3:9, 4:11, 5:12, 6:13

Sorted start times: 2:0, 1:1, 4:1, 3:7, 5:9, 6:10

Merged sequence:
2:0, 1:1, 4:1,1:5,3:7,2:8,3:9,5:9,6:10, 4:11,5:12, 6:13

DP from WAS-1: Preprocessing

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Considering the set of activities S, we start by a pre-processing phase:

- Sort the activities by increasing values of finish times.
- Compute the values $p[i]$,
- This can be done in $O(n \lg n)$

DP from WAS-1: Memoization

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Assuming that tasks are sorted and all $p(i)$ are computed and tabulated in $P[1 \cdots n]$

We keep a table $W[n+1]$, at the end $W[i]$ will hold the weight of an optimal solution for subproblem $\{1, \ldots, i\}$. Initially, set all entries to -1 and $W[0] = 0$.

WAS-2 (j)
if $W[j] ! = -1$ **then**
  return $(W[j])$
else
  $W[j] = \max(w_j + \textbf{WAS-2}(P[j])), \textbf{WAS-2}(j-1))$
  return $W[j]$

DP from WAS-1: Memoization

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if $W[j]! = -1$ **then**
  return $(W[j])$
else
  $W[j] = \max(w_j + \textbf{WAS-2}(P[j])), \textbf{WAS-2}(j-1))$
  return $W[j]$

No subproblem is solved more than once, so cost is $O(n \log + n) = O(n \log n)$

DP from WAS-1: Iterative

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DP from WAS-1: Iterative

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We assume that tasks are sorted and all $p(i)$ are computed and tabulated in $P[1 \cdots n]$

We keep a table $W[n+1]$, at the end $W[i]$ will hold the weight of an optimal solution for subproblem $\{1, \ldots, i\}$.

WAS-3 (n)
$W[0] = 0$
for $j = 1$ to n **do**
  $W[j] = \max(W[P[j]] + w_j, W[j-1])$
return $W[n]$

Time complexity: $O(n \lg n + n)$.
Notice: Both algorithms gave only the numerical max. weight
We recover a solution form $W[n]$.

DP from WAS-2 (-3): Returning an optimal solution

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To get also the list of activities in an optimal solution, we use W and p.

DP from WAS-2 (-3): Returning an optimal solution

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To get also the list of activities in an optimal solution, we use W and p.

Find-Opt (j)
if $j = 0$ **then**
  return $\emptyset$
else if $W[p[j]] + w_j > W[j-1]$ **then**
  return $(\{j\} \cup \text{Find-Opt}(p[j]))$
else
  return $(\text{Find-Opt}(j-1))$

Time complexity: $O(n)$

DP for Weighted Activity Selection

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- We started from a suitable recursive algorithm, which runs $O(2^n)$ but solves only $O(n)$ different subproblemes.
- Perform some preprocesing.
- Compute the weight of an optimal solution to each of the $O(n)$ subproblems.
- Guided by optimal value, obtain an optimal solution .

0-1 Knapsack

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(This example is from Section 6.4 in Dasgupta,Papadimritriou,Vazirani's book.)

0-1 Knapsack: Given as input a set of n items that can NOT be fractioned, item i has weight w_i and value v_i, and a maximum permissible weight W.

QUESTION: select a set of items S that maximize the profit.

Recall that we can NOT take fractions of items.

Subproblems and recurrence

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Input: $(w_1, \ldots, w_n)$, $(v_1, \ldots, v_n)$, W.

- Let $S \subseteq \{1, \ldots, n\}$ be an optimal solution to the problem The optimal benefit is $\sum_{i \in S} v_i$

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Input: $(w_1, \ldots, w_n)$, $(v_1, \ldots, v_n)$, W.

- Let $S \subseteq \{1, \ldots, n\}$ be an optimal solution to the problem The optimal benefit is $\sum_{i \in S} v_i$
- With respect to the last item we have two cases:
  - $n \notin S$, then S is an optimal solution to the problem $(w_1, \ldots, w_{n-1})$, $(v_1, \ldots, v_{n-1})$, W
  - $n \in S$, then $S - \{n\}$ is an optimal solution to the problem $(w_1, \ldots, w_{n-1})$, $(v_1, \ldots, v_{n-1})$, $W - w_n$

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- in both cases we get an optimal solution of a subproblem in which the last item is removed and in which the maximum weight can be W or a value smaller than W.

Subproblems and recurrence

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  - $n \in S$, then $S - \{n\}$ is an optimal solution to the problem $(w_1, \ldots, w_{n-1})$, $(v_1, \ldots, v_{n-1})$, $W - w_n$
- in both cases we get an optimal solution of a subproblem in which the last item is removed and in which the maximum weight can be W or a value smaller than W.
- This identifies subproblems of the form $[i, x]$ that are knapsack instances in which the set of items is $\{1, \ldots, i\}$ and the maximum weight that can hold the knapsack is x.

Subproblems and recurrence

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Let $v[i, x]$ be the maximum value (optimum) we can get from objects $\{1, 2, \ldots, i\}$ within total weight $\leq x$.

Subproblems and recurrence

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Let $v[i, x]$ be the maximum value (optimum) we can get from objects $\{1, 2, \ldots, i\}$ within total weight $\leq x$.

To compute $v[i, x]$, the two possibilities we have considered give raise to the recurrence:

$$v[i, x] = \begin{cases} 0 & \text{if } i = 0 \text{ or } w = 0 \\ v[i-1, x] & \text{if } w_i > x \\ \max v[i-1, x - w_i] + v_i, v[i-1, x] & \text{otherwise} \end{cases}$$

DP algorithm: tabulating

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Define a table $P[n+1, W+1]$ to hold optimal values for the corresponding subproblem.

Knapsack(i, x)
for $i = 0$ **to** n **do**
  $P[i, 0] = 0$
for $x = 1$ **to** W **do**
  $P[0, x] = 0$
for $i = 1$ **to** n **do**
  for $x = 1$ **to** W **do**
    $P[i, x] = \max\{P[i-1, x], P[i-1, x-w[i]] + v[i]\}$
return $P[n, W]$

The number of steps is $O(nW)$

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Define a table $P[n+1, W+1]$ to hold optimal values for the corresponding subproblem.

Knapsack(i, x)
for $i = 0$ **to** n **do**
  $P[i, 0] = 0$
for $x = 1$ **to** W **do**
  $P[0, x] = 0$
for $i = 1$ **to** n **do**
  for $x = 1$ **to** W **do**
    $P[i, x] = \max\{P[i-1, x], P[i-1, x-w[i]] + v[i]\}$
return $P[n, W]$

The number of steps is $O(nW)$ which is

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Define a table $P[n+1, W+1]$ to hold optimal values for the corresponding subproblem.

Knapsack(i, x)
for $i = 0$ **to** n **do**
  $P[i, 0] = 0$
for $x = 1$ **to** W **do**
  $P[0, x] = 0$
for $i = 1$ **to** n **do**
  for $x = 1$ **to** W **do**
    $P[i, x] = \max\{P[i-1, x], P[i-1, x-w[i]] + v[i]\}$
return $P[n, W]$

The number of steps is $O(nW)$ which is pseudopolynomial.

An example

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i	1	2	3	4	5
w_i	1	2	5	6	7
v_i	1	6	18	22	28

$W = 11$.

		w											
		0	1	2	3	4	5	6	7	8	9	10	11
	0	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
	2	0	1	6	7	7	7	7	7	7	7	7	7
I	3	0	1	6	7	7	18	19	24	25	25	25	25
	4	0	1	6	7	7	18	22	23	28	29	29	40
	5	0	1	6	7	7	18	22	28	29	34	35	40

For instance, $v[4, 10] = \max\{v[3, 10], v[3, 10 - 6] + 22\} = \max\{25, 7 + 22\} = 29$.
$v[5, 11] = \max\{v[4, 11], v[4, 11 - 7] + 28\} = \max\{40, 4 + 28\} = 40$.

Recovering the solution

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To compute the actual subset $S \subseteq I$ that is the solution, we modify the algorithm to compute also a Boolean table $K[n+1, W+1]$, so that $K[i, x]$ is 1 when the max is attained in the second alternative ($i \in S$), 0 otherwise.

Recovering the solution

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To compute the actual subset $S \subseteq I$ that is the solution, we modify the algorithm to compute also a Boolean table $K[n+1, W+1]$, so that $K[i, x]$ is 1 when the max is attained in the second alternative ($i \in S$), 0 otherwise.

```
Knapsack(i, x)
for i = 0 to n do
    P[i, 0] = 0; K[i, 0] = 0
for  x = 1 to W do
    P[0, x] = 0; K[0, x] = 0
for i = 1 to n do
    for  x = 1 to W do
        if P[i − 1, x] ≥
        P[i − 1, x − w[i]] + v[i] then
            P[i, x] = P[i − 1, x];
            K[i, x] = 0
        else
            P[i, x] =
            P[i − 1, x − w[i]] + v[i];
            K[i, x] = 1
return  P[n, W]
```

Complexity: $O(nW)$

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	0	1	2	3	4	5	6	7	8	9	10	11
0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0
1	0 0	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1
2	0 0	1 0	6 1	7 1	7 1	7 1	7 1	7 1	7 1	7 1	7 1	7 1
3	0 0	1 0	6 0	7 0	7 0	18 1	19 1	24 1	25 1	25 1	25 1	25 1
4	0 0	1 0	6 0	7 0	7 0	18 1	22 1	23 1	28 1	29 1	29 1	40 1
5	0 0	1 0	6 0	7 0	7 0	18 0	22 0	28 1	29 1	34 1	35 1	40 0

Recovering the solution

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- To compute an optimal solution $S \subseteq I$, we use K to trace backwards the elements in the solution.
- $K[i, x]$ is 1 when the max is attained in the second alternative: $i \in S$.

Recovering the solution

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- To compute an optimal solution $S \subseteq I$, we use K to trace backwards the elements in the solution.
- $K[i, x]$ is 1 when the max is attained in the second alternative: $i \in S$.

$x = W$, $S = \emptyset$
for $i = n$ **downto** 1 **do**
  if $K[i, x] = 1$ **then**
    $S = S \cup \{i\}$
    $x = x - w_i$
Output S

Complexity: $O(nW)$

An example

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i	1	2	3	4	5
w_i	1	2	5	6	7
v_i	1	6	18	22	28

$W = 11$.

An example

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i	1	2	3	4	5
w_i	1	2	5	6	7
v_i	1	6	18	22	28

$W = 11$.

	0	1	2	3	4	5	6	7	8	9	10	11
0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0
1	0 0	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1
2	0 0	1 0	6 1	7 1	7 1	7 1	7 1	7 1	7 1	7 1	7 1	7 1
3	0 0	1 0	6 0	7 0	7 0	18 1	19 1	24 1	25 1	25 1	25 1	25 1
4	0 0	1 0	6 0	7 0	7 0	18 1	22 1	23 1	28 1	29 1	29 1	40 1
5	0 0	1 0	6 0	7 0	7 0	18 0	22 0	28 1	29 1	34 1	35 1	40 0

$K[5, 11] \to K[4, 11] \to K[3, 5] \to K[2, 0]$. So $S = \{4, 3\}$

Complexity

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The 0-1 KNAPSACK is NP-complete.

- 0-1 KNAPSACK, has complexity $O(nW)$, and its length is $O(n \lg M)$ taking $M = \max\{W, \max_i w_i, \max_i v_i\}$.
- If W requires k bits, the cost and space of the algorithm is $n2^k$, exponential in the length W. However the DP algorithm works fine when $W = \Theta(n)$, here $k = O(\log n)$.
- Consider the unary knapsack problem, where all integers are coded in unary (7=1111111). In this case, the complexity of the DP algorithm is polynomial on the size, i.e., UNARY KNAPSACK $\in$P.

Matching DNA sequences

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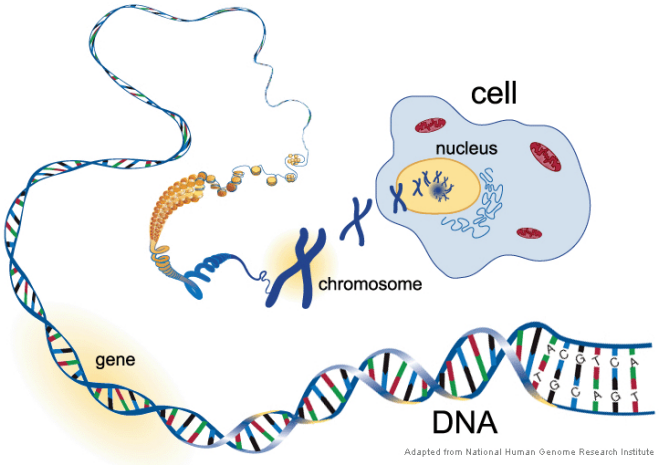

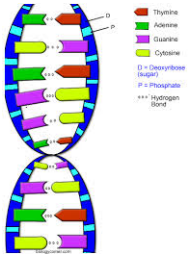

- DNA, is the hereditary material in almost all living organisms. They can reproduce by themselves.
- Its function is like a program unique to each individual organism that rules the working and evolution of the organism.
- Model as a string of 3×10^9 characters over $\{A, T, G, C\}$.

Computational genomics: Some questions

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- When a new gene is discovered, one way to gain insight into its working, is to find well known genes (not necessarily in the same species) which match it closely. Biologists suggest a generalization of edit distance as a definition of approximately match.
- GenBank (`https://www.ncbi.nlm.nih.gov/genbank/`) has a collection of $> 10^{10}$ well studied genes, BLAST is a software to do fast searching for similarities between a gene an those in a DB of genes.
- Sequencing DNA: consists in the determination of the order of DNA bases, in a short sequence of 500-700 characters of DNA. To get the global picture of the whole DNA chain, we generate a large amount of DNA sequences and try to assembled them into a coherent DNA sequence. This last part is usually a difficult one, as the position of each sequence is the global DNA chain is not know before hand.

Evolution DNA

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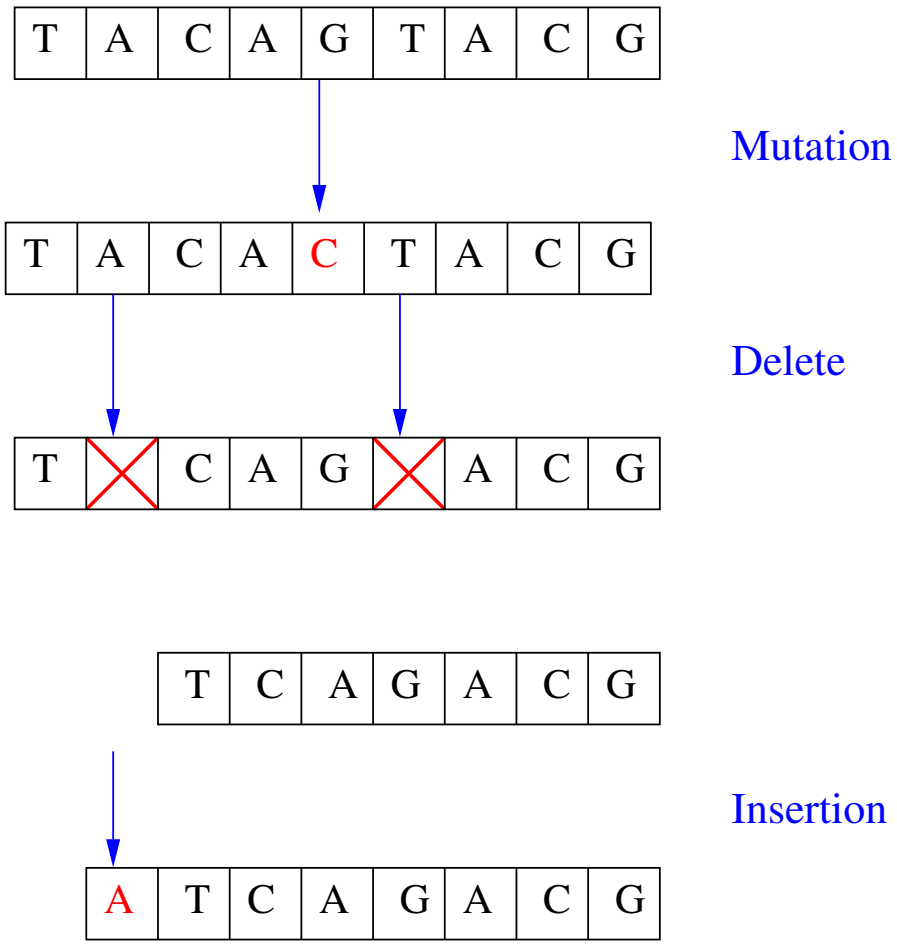

How to compare sequences?

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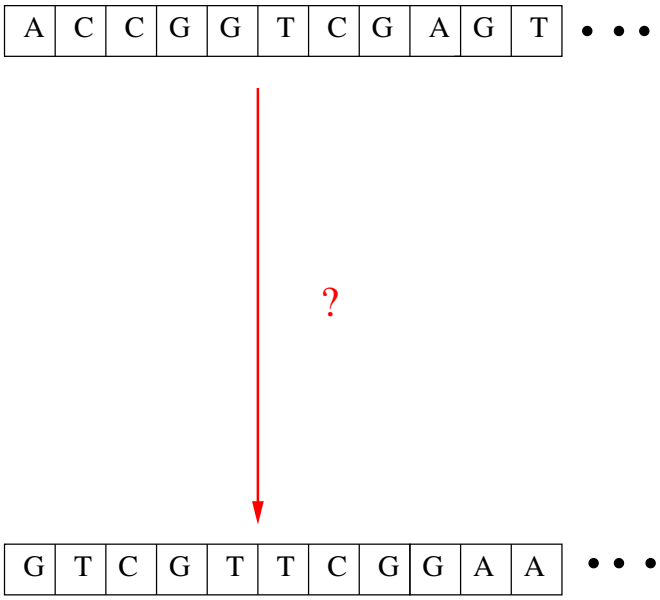

Three problems

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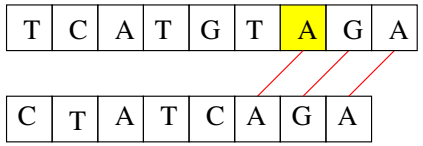
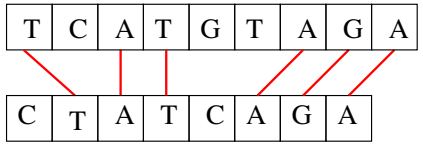
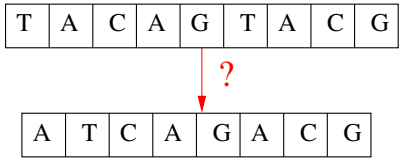
Longest common substring: Substring = consecutive characters in the string.



Longest common subsequence: Subsequence = ordered chain of characters (might have gaps).



Edit distance: Convert one string into another one using a given set of operations.



The Edit Distance problem

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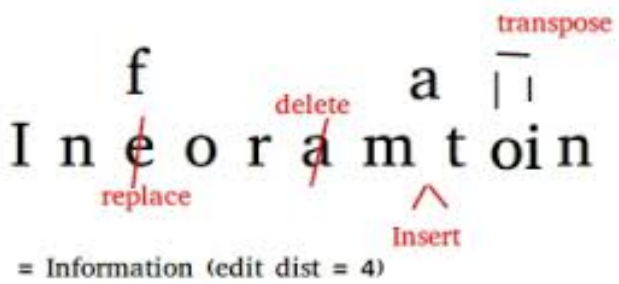
(Section 6.3 in Dasgupta, Papadimritriou, Vazirani's book.)



The edit distance between strings $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ is defined to be the minimum number of *edit operations* needed to transform X into Y.

All the operations are done on X

Edit distance: Applications

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- Computational genomics: evolution between generations, i.e. between strings on $\{A, T, G, C, -\}$.
- Natural Language Processing: distance, between strings on the alphabet.
- Text processor, suggested corrections

Edit Distance: Levenshtein distance

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In the Levenshtein distance the set of operations are

- insert$(X, i, a) = x_1 \cdots x_i a x_{i+1} \cdots x_n$.
- delete$(X, i) = x_1 \cdots x_{i-1} x_{i+1} \cdots x_n$
- modify$(X, i, a) = x_1 \cdots x_{i-1} a x_{i+1} \cdots x_n$.

the cost of modify is 2, and the cost of insert/delete is 1.

To simplify, in the following we assume that *the cost of each operation is 1.*

For other operations and costs the structure of the DP will be similar.

Exemple-1

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$X = aabab$ and $Y = babb$

$aabab = X$

$X' =$insert$(X, 0, b)$ $baabab$

$X'' =$delete$(X', 2)$ $babab$

$X'' =$delete$(X'', 4)$ $babb$

$X = aabab \rightarrow Y = babb$

Exemple-1

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$X = aabab$ and $Y = babb$

$aabab = X$

$X' =$insert$(X, 0, b)$ $baabab$

$X'' =$delete$(X', 2)$ $babab$

$X'' =$delete$(X'', 4)$ $babb$

$X = aabab \rightarrow Y = babb$

A shortest edit distance

$aabab = X$

$X' =$modify$(X, 1, b)$ $babab$

$Y =$delete$(X', 4)$ $babb$

Use dynamic programming.

The structure of an optimal solution

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- In a solution O with minimum edit distance from $X = x_1 \cdots x_n$ to $Y = y_1 \cdots y_m$, we have three possible alignments for the last terms

(1)	(2)	(3)
x_n	$-$	x_n
$-$	y_m	y_m

- In (1), O performs delete x_n, and it transforms optimally, $x_1 \cdots x_{n-1}$ into $y_1 \cdots y_m$.
- In (2), O performs insert y_m at the end of x, and it transforms optimally, $x_1 \cdots x_n$ into $y_1 \cdots y_{m-1}$.
- In (3), if $x_n \neq y_m$, O performs modify x_n by y_m, otherwise O, aligns them without cost. Furthermore O transforms optimally $x_1 \cdots x_{n-1}$ into $y_1 \cdots y_{m-1}$.

The recurrence

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Let $X[i] = x_1 \cdots x_i$, $Y[j] = y_1 \cdots y_j$.
$E[i,j]$ = edit distance from $X[i]$ to $Y[j]$ is the maximum of

- I *put y_j at the end of x*: $E[i, j-1] + 1$
- D *delete x_i*: $E[i-1, j] + 1$
- if $x_i \neq y_j$, M *change x_i into y_j*: $E[i-1, j-1] + 1$, otherwise $E[i-1, j-1]$

Edit distance: Recurrence

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Adding the base cases, we have the recurrence

$$E[i,j] = \begin{cases} j & \text{if } i = 0 \text{ (converting } \lambda \to Y[j]) \\ i & \text{if } j = 0 \text{ (converting } X[i] \to \lambda) \\ \min \begin{cases} E[i-1,j]+1 & \text{if D} \\ E[i,j-1]+1, & \text{if I} \\ E[i-1,j-1]+\delta(x_i,y_j) & \text{otherwise} \end{cases} \end{cases}$$

where

$$\delta(x_i,y_j) = \begin{cases} 0 & \text{if } x_i = y_j \\ 1 & \text{otherwise} \end{cases}$$

Computing the optimal costs and pointers

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Edit(X, Y)
for $i = 0$ **to** n **do**
  $E[i, 0] = i$
for $j = 0$ **to** m **do**
  $E[0, j] = j$
for $i = 1$ **to** n **do**
  for $j = 1$ **to** m **do**
    $\delta = 0$
    if $x_i \neq y_j$ **then**
      $\delta = 1$
    $E[i, j] = E[i, j-1] + 1$ $b[i, j] = \uparrow$
    if $E[i-1, j-1] + \delta < E[i, j]$ **then**
      $E[i, j] = E[i-1, j-1] + \delta$, $b[i, j] := \nwarrow$
    if $E[i-1, j] + 1 < E[i, j]$ **then**
      $E[i, j] = E[i-1, j] + 1$, $b[i, j] := \leftarrow$

Space and time complexity: $O(nm)$.

$\leftarrow$ is a I operation, $\uparrow$ is a D operation, and $\nwarrow$ is either a M or a no-operation.

Computing the optimal costs: Example

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X=aabab; Y=babb. Therefore, $n = 5, m = 4$

		0 λ	1 b	2 a	3 b	4 b
0	λ	0	$\leftarrow$ 1	$\leftarrow$ 2	$\leftarrow$ 3	$\leftarrow$ 4
1	a	$\uparrow$ 1	$\nwarrow$ 1	$\nwarrow$ 1	$\leftarrow$ 2	$\leftarrow$ 3
2	a	$\uparrow$ 2	$\nwarrow$ 2	$\nwarrow$ 1	$\leftarrow$ 2	$\leftarrow$ 3
3	b	$\uparrow$ 3	$\nwarrow$ 2	$\uparrow$ 2	$\nwarrow$ 1	$\nwarrow$ 2
4	a	$\uparrow$ 4	$\uparrow$ 3	$\nwarrow$ 2	$\uparrow$ 2	$\nwarrow$ 2
5	b	$\uparrow$ 5	$\nwarrow$ 4	$\uparrow$ 3	$\uparrow$ 2	$\nwarrow$ 2

$\leftarrow$ is a I operation, $\uparrow$ is a D operation, and
$\nwarrow$ is either a M or a no-operation.

Obtain Y in edit distance from X

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Uses as input the arrays E and b.
The first call to the algorithm is **con-Edit** (n, m)

con-Edit(i, j)
if $i = 0$ or $j = 0$ **then**
  return
  if $b[i, j] = \nwarrow$ and $x_i = y_j$ **then**
    change(X, i, y_j)); **con-Edit**$(i - 1, j - 1)$
  if $b[i, j] = \uparrow$ **then**
    delete(X, i); **con-Edit**$(i - 1, j)$
  if $b[i, j] = \leftarrow$ **then**
    insert(X, i, y_j), **con-Edit**$(i, j - 1)$

This algorithm has time complexity $O(nm)$.

The Longest Common Subsequence

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(Section 15.4 in CormenLRS' book.)

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(Section 15.4 in CormenLRS' book.)

- $Z = z_1 \cdots z_k$ is a subsequence of X if there is a subsequence of integers $1 \leq i_1 < i_2 < \ldots < i_k \leq n$ such that $z_j = x_{i_j}$.

  TTT is a subsequence of $ATATAT$.

The Longest Common Subsequence

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(Section 15.4 in CormenLRS' book.)

- $Z = z_1 \cdots z_k$ is a subsequence of X if there is a subsequence of integers $1 \leq i_1 < i_2 < \ldots < i_k \leq n$ such that $z_j = x_{i_j}$.

  TTT is a subsequence of $ATATAT$.
- If Z is a subsequence of X and Y, then Z is a common subsequence of X and Y.

The Longest Common Subsequence

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(Section 15.4 in CormenLRS' book.)

- $Z = z_1 \cdots z_k$ is a subsequence of X if there is a subsequence of integers $1 \leq i_1 < i_2 < \ldots < i_k \leq n$ such that $z_j = x_{i_j}$.

  TTT is a subsequence of $ATATAT$.
- If Z is a subsequence of X and Y, then Z is a common subsequence of X and Y.

LCS Given sequences $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$, compute the longest common subsequence Z.

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common subsequence (lcs). Then,

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common subsequence (lcs). Then,

- $Z = x_{i_1} \ldots x_{i_k} = y_{j_1} \ldots y_{j_k}$

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common subsequence (lcs). Then,

- $Z = x_{i_1} \ldots x_{i_k} = y_{j_1} \ldots y_{j_k}$
- There are no i, j, with $i > i_k$ and $j > j_k$, s.t. $x_i = y_j$. Otherwise, Z will not be optimal.

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common subsequence (lcs). Then,

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- $a = x_{i_k}$ might appear after i_k in X, but not after j_k in Y, or viceversa.

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common subsequence (lcs). Then,

- $Z = x_{i_1} \ldots x_{i_k} = y_{j_1} \ldots y_{j_k}$
- There are no i, j, with $i > i_k$ and $j > j_k$, s.t. $x_i = y_j$. Otherwise, Z will not be optimal.
- $a = x_{i_k}$ might appear after i_k in X, but not after j_k in Y, or viceversa.
- There is an optimal solution in which i_k and j_k are the last occurrence of a in X and Y respectively.

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let $Z = x_{i_1} \ldots x_{i_k} = y_{j_1} \ldots y_{j_k}$ a lcs s.t. the index of the final common symbol in Z is its last occurrence in both X and Y.

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let $Z = x_{i_1} \ldots x_{i_k} = y_{j_1} \ldots y_{j_k}$ a lcs s.t. the index of the final common symbol in Z is its last occurrence in both X and Y.

Let $X^- = x_1 \cdots x_{n-1}$ and $Y^- = y_1 \cdots y_{m-1}$

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let $Z = x_{i_1} \ldots x_{i_k} = y_{j_1} \ldots y_{j_k}$ a lcs s.t. the index of the final common symbol in Z is its last occurrence in both X and Y.

Let $X^- = x_1 \cdots x_{n-1}$ and $Y^- = y_1 \cdots y_{m-1}$

- Let us look at x_n and y_m.
- If $x_n = y_m$, $i_k = n$ and $j_k = m$ so, $x_{i_1} \ldots x_{i_{k-1}}$ is a lcs of X^- and Y^-.

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let $Z = x_{i_1} \ldots x_{i_k} = y_{j_1} \ldots y_{j_k}$ a lcs s.t. the index of the final common symbol in Z is its last occurrence in X and Y.

Let $X^- = x_1 \cdots x_{n-1}$ and $Y^- = y_1 \cdots y_{m-1}$

- Let us look at x_n and y_m.
- If $x_n \neq y_m$,

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Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let $Z = x_{i_1} \ldots x_{i_k} = y_{j_1} \ldots y_{j_k}$ a lcs s.t. the index of the final common symbol in Z is its last occurrence in X and Y.

Let $X^- = x_1 \cdots x_{n-1}$ and $Y^- = y_1 \cdots y_{m-1}$

- Let us look at x_n and y_m.
- If $x_n \neq y_m$,
  - If $i_k < n$ and $j_k < m$, Z is a lcs of X^- and Y^-.
  - If $i_k = n$ and $j_k < m$, Z is a lcs of X and Y^-.
  - If $i_k <$ and $j_k = m$, Z is a lcs of X^- and Y.
  - The last two include the first one!

DP approach: Supproblems

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Subproblems = lcs of pairs of prefixes of the initial strings.

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Subproblems = lcs of pairs of prefixes of the initial strings.

Notation:

- $X[i] = x_1 \dots x_i$, for $0 \leq i \leq n$
- $Y[j] = y_1 \dots y_j$, for $0 \leq j \leq m$
- $c[i, j]$ = length of the LCS of $X[i]$ and $Y[j]$.
- Want $c[n, m]$ i.e. length of the LCS for X and Y.

DP approach: Recursion

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Therefore, given X and Y

$$c[i,j] = \begin{cases} 0 & \text{if } i = 0 \text{ or } j = 0 \\ c[i-1, j-1] + 1 & \text{if } x_i = y_j \\ \max(c[i, j-1], c[i-1, j]) & \text{otherwise} \end{cases}$$

The recursive algorithm

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$\mathbf{LCS}(X, Y)$
$n = X.size(); \; m = Y.size()$
if $n = 0$ or $m = 0$ **then**
  return 0
else if $x_n = y_m$ **then**
  return $1 + \mathbf{LCS}(X^-, Y^-)$
else
  return $\max\{\mathbf{LCS}(X, Y^-), \mathbf{LCS}(X^-, Y)\}$

The recursive algorithm

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LCS(X, Y)
$n = X.size()$; $m = Y.size()$
if $n = 0$ or $m = 0$ **then**
  return 0
else if $x_n = y_m$ **then**
  return $1+$**LCS**(X^-, Y^-)
else
  return $\max\{$**LCS**(X, Y^-), **LCS**$(X^-, Y)\}$

The algorithm makes 1 or 2 recursive calls and explores a tree of depth $O(n+m)$, therefore the time complexity is $2^{O(n+m)}$.

DP: tabulating

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We need to find the correct traversal of the table holding the $c[i, j]$ values.

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We need to find the correct traversal of the table holding the $c[i,j]$ values.

- Base case is $c[0,j] = 0$, for $0 \leq j \leq m$, and $c[i,0] = 0$, for $0 \leq i \leq n$.
- To compute $c[i,j]$, we have to access

$c[i-1,j-1]$	$c[i-1,j]$
$c[i,j-1]$	$c[i,j]$

  A row traversal provides a correct ordering.
- To being able to recover a solution we use a table b, to indicate which one of the three options provided the value $c[i,j]$.

Tabulating

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LCS(X, Y)
for $i = 0$ **to** n **do**
  $c[i, 0] = 0$
for $j = 1$ **to** m **do**
  $c[0, j] = 0$
for $i = 1$ **to** n **do**
  for $j = 1$ **to** m **do**
    if $x_i = y_j$ **then**
      $c[i, j] = c[i-1, j-1] + 1,\ b[i.j] = \nwarrow$
    else if $c[i-1, j] \geq c[i, j-1]$ **then**
      $c[i, j] = c[i-1, j],\ b[i, j] = \leftarrow$
    else
      $c[i, j] = c[i, j-1],\ b[i, j] = \uparrow.$

complexity:
$T = O(nm)$.

Example.

X=(ATCTGAT); Y=(TGCATA). Therefore, $m = 6, n = 7$

		0	1 T	2 G	3 C	4 A	5 T	6 A
0		0	0	0	0	0	0	0
1	A	0	↑0	↑0	↑0	↖1	←1	↖1
2	T	0	↖1	←1	←1	↑1	↖2	←2
3	C	0	↑1	↑1	↖2	←2	↑2	↑2
4	T	0	↖1	↑1	↑2	↑2	↖3	←3
5	G	0	↑1	↖2	↑2	↑2	↑3	↑3
6	A	0	↑1	↑2	↑2	↖3	↑3	↖4
7	T	0	↖1	↑2	↑2	↑3	↖4	↑4

Following the arrows: TCTA

Construct the solution

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Access the tables c and d.

The first call to the algorithm is **sol-LCS**(n, m)

sol-LCS(i, j)
if $i = 0$ or $j = 0$ **then**
  STOP.
else if $b[i, j] = \nwarrow$ **then**
  sol-LCS$(i - 1, j - 1)$
  return x_i
else if $b[i, j] = \uparrow$ **then**
  sol-LCS$(i - 1, j)$
else
  sol-LCS$(i, j - 1)$

The algorithm has time complexity $O(n + m)$.

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- A slightly different problem with a similar solution

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- A slightly different problem with a similar solution
- LCSt: Given two strings $X = x_1 \dots x_n$ and $Y = y_1 \dots y_m$, compute their longest common substring Z, i.e., the largest k for which there are indices i and j with $x_i x_{i+1} \dots x_{i+k} = y_j y_{j+1} \dots y_{j+k}$.

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- A slightly different problem with a similar solution
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- For example:
  X : DEADBEEF
  Y : EATBEEF
  Z :

Longest common substring

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- A slightly different problem with a similar solution
- LCSt Given two strings $X = x_1 \dots x_n$ and $Y = y_1 \dots y_m$, compute their longest common substring Z, i.e., corresponding to the largest k for which there are indices i and j with $x_i x_{i+1} \dots x_{i+k} = y_j y_{j+1} \dots y_{j+k}$.
- For example:
  X : DEADBBEEF
  Y : EATBEEF
  Z :

Longest common substring

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- A slightly different problem with a similar solution
- LCSt Given two strings $X = x_1 \dots x_n$ and $Y = y_1 \dots y_m$, compute their longest common substring Z, i.e., corresponding to the largest k for which there are indices i and j with $x_i x_{i+1} \dots x_{i+k} = y_j y_{j+1} \dots y_{j+k}$.
- For example:
  X : DEADBBEEF
  Y : EATBEEF
  Z : BEEF pick the longest substring

Characterization of optimal solution

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- Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common substring.
  - $Z = x_i \ldots x_{i+k} = y_j \ldots y_{j+k}$

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- Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common substring.
  - $Z = x_i \ldots x_{i+k} = y_j \ldots y_{j+k}$
  - Z is the longest common suffix of $X(i+k)$ and $Y(j+k)$.

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- Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common substring.
  - $Z = x_i \ldots x_{i+k} = y_j \ldots y_{j+k}$
  - Z is the longest common suffix of $X(i+k)$ and $Y(j+k)$.
- We can consider the subproblems $LCStf(i,j)$: compute the longest common suffix of $X(i)$ and $Y(j)$.

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- Let $X = x_1 \cdots x_n$ and $Y = y_1 \cdots y_m$ and let Z be a longest common substring.
  - $Z = x_i \ldots x_{i+k} = y_j \ldots y_{j+k}$
  - Z is the longest common suffix of $X(i+k)$ and $Y(j+k)$.
- We can consider the subproblems $LCStf(i,j)$: compute the longest common suffix of $X(i)$ and $Y(j)$.
- The $LCSf(X,Y)$ is the longest of such common suffixes.

Computing the LC Suffixes

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- To solve $LCSf(i, j)$ it is enough to go backward from position i in X and j in Y until we find two different characters.
- This has cost $O(n + m)$ per subproblem.

Computing the LC Suffixes

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- To solve $LCSf(i, j)$ it is enough to go backward from position i in X and j in Y until we find two different characters.
- This has cost $O(n + m)$ per subproblem.
- We get a $O(nm(n + m))$ algorithm for LCSt

Computing the LC Suffixes

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- To solve $LCSf(i, j)$ it is enough to go backward from position i in X and j in Y until we find two different characters.
- This has cost $O(n + m)$ per subproblem.
- We get a $O(nm(n + m))$ algorithm for LCSt
- Can we do it faster?

Computing the LC Suffixes

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- To solve $LCSf(i, j)$ it is enough to go backward from position i in X and j in Y until we find two different characters.
- This has cost $O(n + m)$ per subproblem.
- We get a $O(nm(n + m))$ algorithm for LCSt
- Can we do it faster? Let us use DP!

A recursive solution for LC Suffixes

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Notation:

- $X[i] = x_1 \dots x_i$, for $0 \leq i \leq n$
- $Y[j] = y_1 \dots y_j$, for $0 \leq j \leq m$
- $s[i, j]$ = the length of the LC Suffix of $X[i]$ and $Y[j]$.
- Want $\max_{i,j} s[i, j]$ i.e., the length of the LCSt of X, Y.

DP approach: Recursion

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Therefore, given X and Y

$$s[i,j] = \begin{cases} 0 & \text{if } i = 0 \text{ or } j = 0 \\ 0 & \text{if } x_i \neq y_j \\ s[i-1, j-1] + 1 & \text{if } x_i = y_j \end{cases}$$

DP approach: Recursion

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Therefore, given X and Y

$$s[i,j] = \begin{cases} 0 & \text{if } i = 0 \text{ or } j = 0 \\ 0 & \text{if } x_i \neq y_j \\ s[i-1, j-1] + 1 & \text{if } x_i = y_j \end{cases}$$

Using the recurrence the cost per recursive call (or per element in the table) is constant

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LCSf(X, Y)
for $i = 0$ **to** n **do**
  $s[i, 0] = 0$
for $j = 1$ **to** m **do**
  $s[0, j] = 0$
for $i = 1$ **to** n **do**
  for $j = 1$ **to** m **do**
    s[i,j]=0
    if $x_i = y_j$ **then**
      $s[i, j] = s[i - 1, j - 1] + 1$

complexity: $O(nm)$.

Which gives an algorithm with cost $O(nm)$ for LCSt