



# CS 590: Algorithms

Design and Analysis Technique

Dynamic Programming and Greedy Algorithms



# Dynamic Programming

# 8. Dynamic Programming

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## Dynamic Programming (Overview):

- It's a **technique** like divide-and-conquer, **not** a specific algorithm.
- Not really refers to computer programming. Developed back in the day when “programming” meant “tabular method”.
- We use it for **optimization** problems.
  - Find a solution with the **optimal value**.
  - Minimization or Maximization (we will do both).
- Four-step method:
  1. **Characterize** the structure of an optimal solution.
  2. **Recursively** define the value of an optimal solution.
  3. **Compute** the value of an optimal solution, typically a bottom-up fashion.
  4. **Construct** an optimal solution from the computed information.

# 8. Dynamic Programming

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Dynamic Programming Examples:

- Rod-cutting
- Longest Common Sequence
- Sequential Alignment – Smith-Waterman Algorithm
- Optimal BSTs

## 8.1. Rod Cutting

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- How do we cut steel rods into pieces in order to maximize the revenue we can get?
- Each cut is free.
- The length of a rod is always an integral number of inches.
  - Input: A length  $n$  and table prices  $p_i$  for  $i = 1, 2, \dots, n$ .
  - Output: The **maximum revenue** we can obtain for rods whose length **sum up to  $n$** , computed as the sum of the prices for the individual rods.  
⇒ If  $p_n$  is **large enough**, then an optimal solution might not require any cuts (we leave them  $n$  inches long).

## 8.1. Rod Cutting

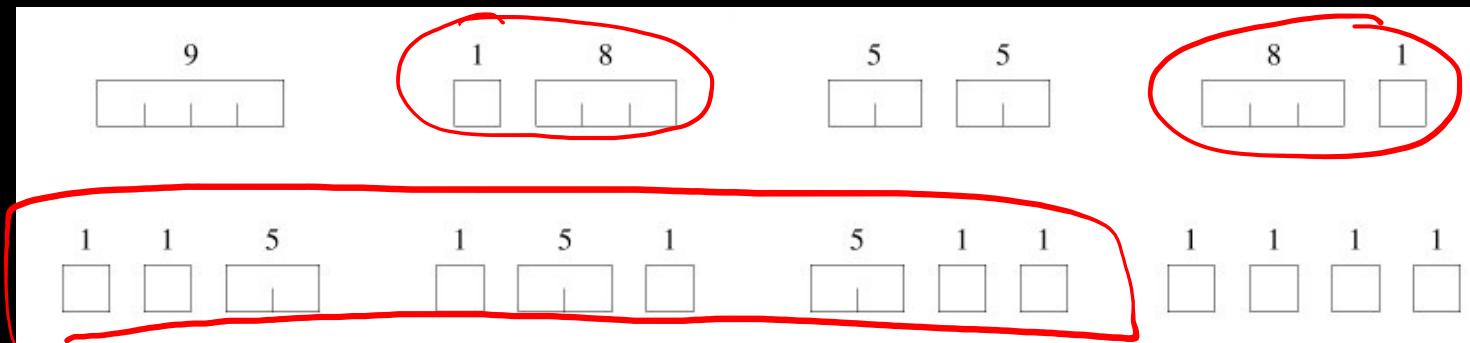
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- Consider the example table below:

Length $i$	1	2	3	4	5	6	7	8
Price $p_i$	1	5	8	9	10	17	17	20

- We can cut the rod  $2^{n-1}$  different ways.
- We can choose to cut or not to cut after each of the first  $n - 1$  inches (binary numbers).
- For example, there are 8 possible ways to cut a rod of length 4.



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- Let  $r_i$  be the **maximum revenue** for a rod of length  $i$ .
- Express a solution as a sum of the individual rod length.
- We can determine the optimal revenues  $r_i$  for the example by inspection:

$i$	$r_i$	optimal solution
1	1	1 (no cuts)
2	5	2 (no cuts)
3	8	3 (no cuts)
4	10	2+2
5	13	2+3
6	17	6 (no cuts)
7	18	1+6 or 2+2+3
8	22	2+6

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Determine the optimal revenue  $r_n$  by taking the maximum of

- $p_n$ : the price we get by not making a cut.
- $r_1 + r_{n-1}$ : the maximum revenue from a rod of 1 inch and a rod of  $n - 1$  inches.
- $r_2 + r_{n-2}$ : the maximum revenue from a rod of 2 inches and a rod of  $n - 2$  inches.
- Until we reach  $r_{n-1} + r_1$ .
- This gives us:

$$r_n = \max(p_n, r_1 + r_{n-1}, r_2 + r_{n-2}, \dots, r_{n-1} + r_1)$$

*no cut*

A red circle highlights the term  $p_n$  in the equation. A green arrow points from the word "no cut" to the circled  $p_n$ .

**Optimal substructure**: To solve original problem of size  $n$ , solve on smaller sizes. We have two subproblems after a cut.

Optimal solution to original problem incorporates optimal solution to subproblems → **Solve subproblems independently.**

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Simpler Way to decompose the problem:

- Every optimal solution has a **leftmost cut**.
- There is a first cut that gives a first piece of length  $i$  cut off the left end.
- The remaining piece of length  $n - i$  is on the right.

Simplified Solution:

- We only need to divide **the remainder**, not the first piece.
- That leaves only **one subproblem**, rather than two subproblems to solve.
- If the solution has **no cuts**, then it has a first piece size of  $i = n$  with revenue  $p_n$  and a remainder size of 0 with  $r_0 = 0$ .
- This gives us a simpler version of the equation for  $r_n$ :

$$r_n = \max_{1 \leq i \leq n} (p_i + r_{n-i})$$

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length $i$	1	2	3	4	5	6	7	8
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$i$	$r_i$	optimal solution
1	1	1 (no cuts)
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Recursive top-down solution:

- Direct implementation of simpler equation for  $r_n$ .
- A call to **CUT-ROD(p, n)** returns the optimal revenue  $r_n$ .

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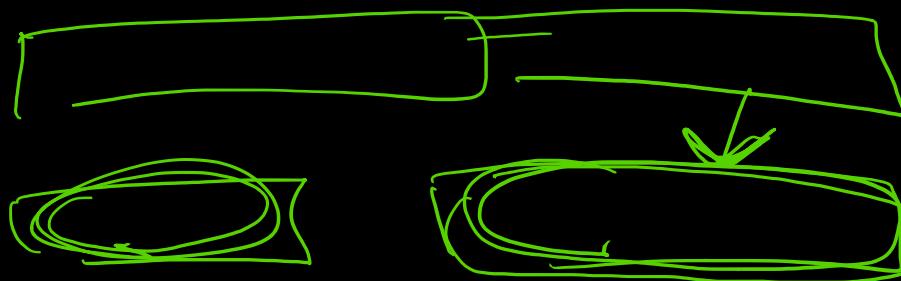


Recursive top-down solution:

- Direct implementation of simpler equation for  $r_n$ .
- A call to **CUT-ROD(p, n)** returns the optimal revenue  $r_n$ .

Algorithm (**CUT-ROD(p, n)**)

```
1      if (n = 0) then
2          return 0
3      q = -∞
4      for (1 ≤ i ≤ n) do
5          q = max (q, p[i] + CUT-ROD (p, n-i))
6      return q
```



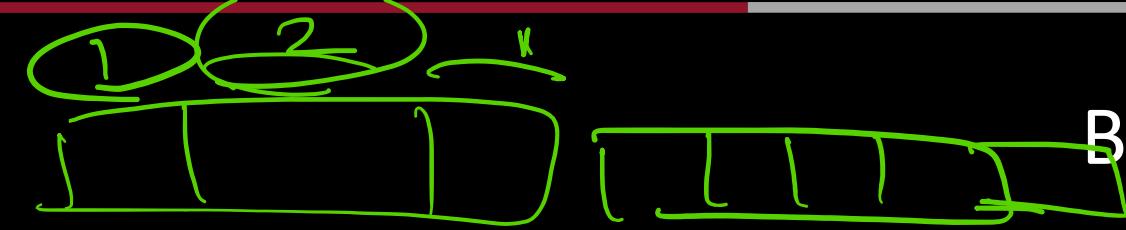
Problem: Our algorithm works, but it is **terribly inefficient**. The running time **doubles** each time  $n$  increases by 1.

- Could take more than an hour for  $n = 40$ .

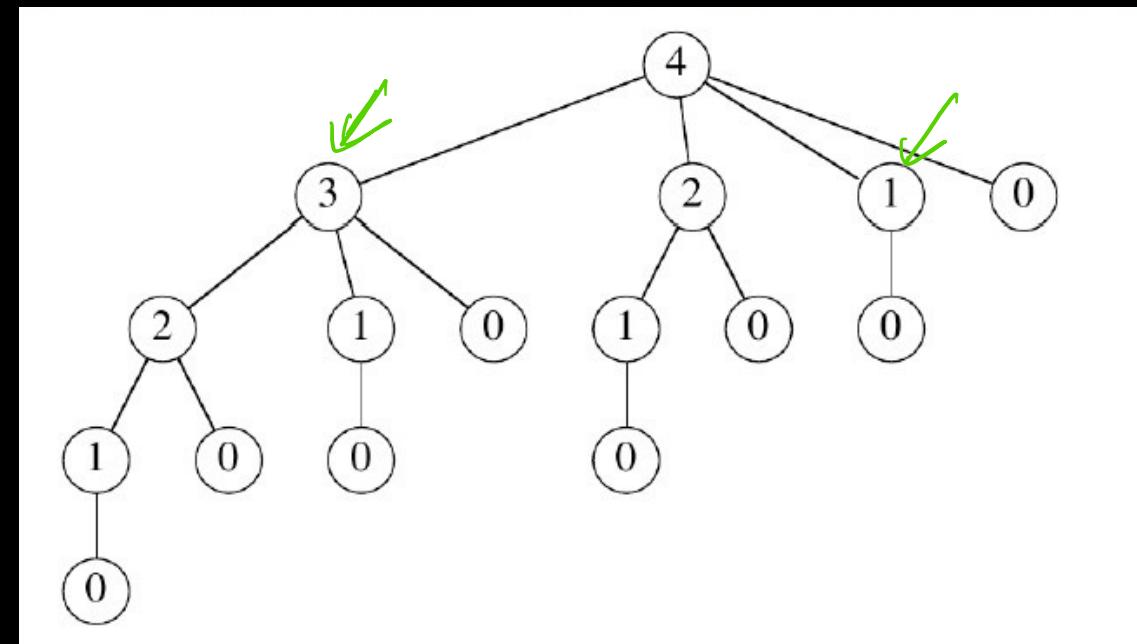
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Inefficient Example:

- **CUT-ROD** calls itself repeatedly, even on subproblems it has **already** solved.
- Tree for  $n = 4$ . Inside each node is the value of  $n$  for the call.



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- Let  $T(n)$  equals the number of calls to CUT-ROD with **second parameter equal to  $n$** .
- The recurrence looks as follows:

$$T(n) = \begin{cases} 1 & \text{if } n = 0 \\ 1 + \sum_{j=0}^{n-1} T(j) & \text{if } n > 1 \end{cases}$$

- The summation counts all calls when the **second** parameter is  $j = n - 1$ .
- Solution of the recurrence is  $T(n) = 2^n$ .

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Dynamic-programming solution:

- Do not solve the **same subproblem** repeatedly.
- Arrange to solve each subproblem **just once**.
- **Save** the solution to a subproblem in a table, and **refer back** to the table whenever you revisit the subproblem.
- The goal is: **store, do not recompute**.
  - Time-memory trade-off
- This method can turn an exponential-time solution into a **polynomial-time** solution.

Two basic approaches:

- Top-down with **memoization**.
- Bottom-up.

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### Top-down with memoization:

- **Memoizing** is remembering what we have computed **previously**.
- Solve the problem **recursively**, but **store** each result in a table.
- In order to find the solution of a subproblem, we first look into this table.
  - If the answer is there, we will just **use** it.
  - Otherwise, we **compute** the solution to the subproblem and then **store** the solution in the table for future use.

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Top-down with memoization:

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  - If the answer is there, we will just **use** it.
  - Otherwise, we **compute** the solution to the subproblem and then **store** the solution in the table for future use.

**Algorithm (MEMOIZED-CUT-ROD(p, n))**

```
1      let r[0, ..., n] be a new array
2      for (0 ≤ i ≤ n) do
3          r[i] = -∞
4      return MEMOIZED-CUT-ROD-AUX(p, n, r)
```

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### Top-down with memoization:

- The memoized version of the recursive solution stores the solution to the subproblem of length  $i$  in the array entry  $r[i]$ .

Algorithm (MEMOIZED-CUT-ROD-AUX( $p$ ,  $n$ ,  $r$ ))

```
1      if (r[n] ≥ 0) then
2          return r[ n ]
3      if ( n = 0 ) then
4          q = 0
5      else
6          q = -∞
7          for (1 ≤ i ≤ n) do
8              q = max(q,p[i]+MEMOIZED-CUT-ROD-AUX (p ,n-i ,r)
9          r[i] = q
10         return q
```

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Bottom-up:

- Sort the subproblems by size.
- Solve the smaller ones first.
- When solving a subproblem, we then already solved the smaller subproblems needed.

Algorithm (BOTTOM-UP-CUT-ROD( $p, n$ ))

```
1      let  $r[0, \dots, n]$  be a new array
2       $r[0] = 0$ 
3      for ( $1 \leq j \leq n$ ) do
4           $q = -\infty$ 
5          for ( $1 \leq i \leq j$ ) do
6               $q = \max(q, p[i]+r[j-i])$ 
7           $r[j] = q$ 
8      return  $r[n]$ 
```

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### Running time:

The top-down (memoized) and the bottom-up algorithms run both in  $\Theta(n^2)$  time.

### Bottom-up:

- We have **doubly nested loops** in BOTTOM-UP-ROD-CUT.
- The number of iterations of the inner loop forms **an arithmetic series**.

### Top-down:

- MEMOIZED-CUT-ROD solves each of the subproblems just **once**, and it solves subproblems for size  $0, 1, \dots, n$ .
- To solve a subproblem of size  $n$ , the for-loop **iterates  $n$  times**  $\Rightarrow$  over all recursive calls, the total number of iterations forms **an arithmetic series**.

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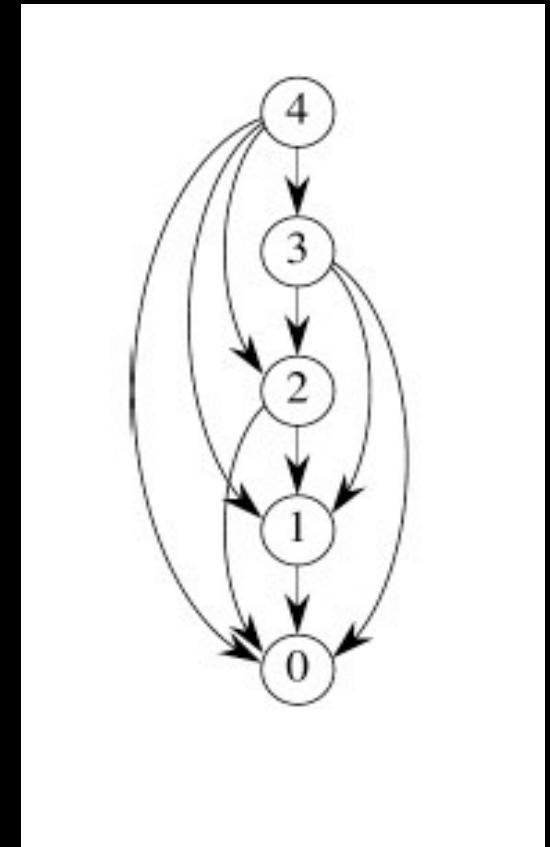
### Subproblem graphs:

**Question:** How do we understand the subproblems that are involved and how they depend on each other?

We use a directed graph:

- **One vertex** for each **distinct subproblem**.
- Has a **direct edge**  $(x, y)$  if computing an optimal solution to the subproblem  $x$  directly requires knowledge of an optimal solution to the subproblem  $y$ .

**Example:** For rod-cutting problem with  $n = 4$ .



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### Subproblem graphs:

- Think of the subproblem graph as a **collapsed version** of the tree of recursive calls.
- All nodes for the same subproblems are collapsed into a **single vertex**.
- All edges go from **parent to child**.
- Subproblem graph can help us to determine the running time.
- Running time is the **sum of times needed to solve each subproblem** (each subproblem solved just once).
  - Time to compute the solution to a subproblem is typically **linear** in the out-degree (number of outgoing edges) of its vertex.
  - Number of subproblems equals **the number of vertices**.
- When these conditions hold, the running time is **linear** in the number of vertices and edges.

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### Reconstructing a solution:

- Focus not only on the value of an optimal solution, rather than the **choices** that produce an optimal solution.
- We extend the bottom-up approach to also **record the optimal choices**.
- We **save** these choices (first cut) in a separable table **s**.
- A separate algorithm will print the optimal choices based on **s**.



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**Algorithm (EXT-BOTTOM-UP-CUT-ROD(p, n))**

```
1  let r[0, ..., n] and s[0, ..., n] be new arrays
2  r[0] = 0
3  for (1 ≤ j ≤ n) do
4      q = -∞
5      for (1 ≤ i ≤ j) do
6          if (q < p[i]+r[j-i]) then
7              q = p[i] + r[j-i]
8              s[j] = i
9              r[j] = q
10 return r and s
```

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Reconstructing a solution:

**Algorithm (PRINT-CUT-ROD-SOLUTION( $p, n$ ))**

```
1   ( $r, s$ ) = EXT-BOTTOM-UP-CUT-ROD ( $p, n$ )
2   while ( $n \geq 0$ ) do
3       print  $s[n]$ 
4        $n = n - s[n]$ 
```

- Call to PRINT-CUT-ROD-SOLUTION( $p, 8$ )

$i$	0	1	2	3	4	5	6	7	8
$r[i]$	0	1	5	8	10	13	17	18	22
$s[i]$	0	1	2	3	2	2	6	1	2

- Call to PRINT-CUT-ROD-SOLUTION( $p, 6$ ):
  - Prints  $s=6$ , sets  $n=0$ , and terminates.

$i$	$r_i$	optimal solution
1	1	1 (no cuts)
2	5	2 (no cuts)
3	8	3 (no cuts)
4	10	2+2
5	13	2+3
6	17	6 (no cuts)
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## 8.2. Longest Common Sequence (LCS)

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- **Problem:** We are given 2 sequences  $X=[x_1, \dots, x_m]$  and  $Y=[y_1, \dots, y_n]$ . We want to find subsequence with the longest length common to both  $X$  and  $Y$ .
- **Subsequence:** A subsequence does not have to be consecutive, but it has to be **in order**.
  
- Search a dictionary for all words that contain we are looking for as a subsequence.
- UNIX command `grep `.*p.*i.*n,*e.*' dict` does search the file `dict` for words with subsequence pine.
- Then we have to check if that word is actually the LCS.



## 8.2. Longest Common Sequence (LCS)

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Example: different types of trees.

s p r i n g t i m e ↗  
p i o n e e r      pine

oak ↗  
h o r s e b a c k  
s n o w f l a k e

elm ↗  
m a e l s t r o m ↗  $X_m$   
b e c a l m ↗  $\tau_n$        $Z_{k-1} = l$   
 $Z_k = m$

holly ↗  
h e r o i c a l l y  
s c h o l a r i y

⇒ subsequences: "pine", "oak", "elm", "holly"

$$Z = \text{elm} \quad X_m = \tau_n = m$$

$$Z_{k-1} = el$$

$$X_{m-1}, \tau_{n-1}$$

## 8.2. Longest Common Sequence (LCS)

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### Brute-force algorithm:

- For every subsequence of X, we check whether it is a subsequence of Y.
- Running time:  $\Theta(n2^m)$ .
  - $2^m$  subsequences of X to check.
  - Each subsequence takes  $\Theta(n)$  time to check: We scan Y for first letter, from there search the second, and so on.

### Optimal substructure:

- Notation:
  - $X_i = \text{prefix}[x_1, \dots, x_i]$
  - $Y_i = \text{prefix}[y_1, \dots, y_i]$

## 8.2. Longest Common Sequence (LCS)

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### Theorem:

Let  $Z = [z_1, \dots, z_k]$  be any LCS of  $X$  and  $Y$ .

1. If  $x_m = y_n$ , then  $z_k = x_m = y_n$  and  $Z_{k-1}$  is an LCS of  $X_{m-1}$  and  $Y_{n-1}$ .
2. If  $x_m \neq y_n$ , then  $z_k \neq x_m \Rightarrow Z$  is an LCS of  $X_{m-1}$  and  $Y$ .
3. If  $x_m \neq y_n$ , then  $z_k \neq y_n \Rightarrow Z$  is an LCS of  $X$  and  $Y_{n-1}$ .

$$X = [x_1, \dots, x_m] \quad Y = [y_1, \dots, y_n].$$

$$Z = [z_1, \dots, z_k]$$

## 8.2. Longest Common Sequence (LCS)

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### Proof of Theorem 1:

- First show that  $\mathbf{z}_k = \mathbf{x}_m = \mathbf{y}_n$ .
- But we now assume that it is not (contradiction).
- Then make a subsequence  $\mathbf{Z}' = [\mathbf{z}_1, \dots, \mathbf{z}_k, \mathbf{x}_m]$ .
- It is a common sequence of X and Y and has length  $k + 1 \Rightarrow \mathbf{Z}'$  is a longer common sequence than Z .
- $\Rightarrow$  contradicts Z being an LCS. ✓
- Now show  $Z_{k-1}$  is an LCS of  $X_{m-1}$  and  $Y_{n-1}$ :
- It is a common sequence. Now, suppose there exists a common sequence  $W$  of  $X_{m-1}$  and  $Y_{n-1}$  that is longer than  $Z_{k-1} \Rightarrow$  the length of  $W \geq k$ .
- Make subsequence  $W'$  by appending  $x_m$  to  $W$ .
- $W'$  is a common sequence of X and Y, has length  $\geq k + 1$
- $\Rightarrow$  Contradicts Z being an LCS. ✓

## 8.2. Longest Common Sequence (LCS)

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### Proof of Theorem 1:

- $X = [m, a, e, l, s, t, r, o, m]$
  - $Y = [b, e, c, a, l, m]$
  - $Z = [e, l]$
  - $Z' = [e, l, m]$
- 
- $Z_{k-1} = [e]$
  - $W = [e, l]$
  - $W' = [e, l, m]$

## 8.2. Longest Common Sequence (LCS)

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### Proof of Theorem 2:

- If  $z_k \neq x_m$ ,
- Then  $Z$  is a common sequence of  $X_{m-1}$  and  $Y$ .
- Suppose there exists a subsequence  $W$  of  $X_{m-1}$  and  $Y$  with length  $> k$ .
- Then  $W$  is a common subsequence of  $X$  and  $Y$ .
- $\Rightarrow$  contradicts  $Z$  being an LCS.

### Proof of Theorem 3:

- Symmetric to 2.

## 8.2. Longest Common Sequence (LCS)

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### Proof of Theorem 2:

- $X = [p, i, o, n, e, e, r], X_{m-1} = [p, i, o, n, e, e]$
- $Y = [s, p, r, i, n, g, t, i, m, e]$
- $z_k = e$  not  $r$
- $Z = [p, i, n, e]$

$Z = \text{LCS of } X_m + Y_n$   
 $Z_c = X_m, Z = \text{pine}.$   
 $X_{m-1} = \text{Pioneer}$

$Y = \text{Springtree}$

$W = \text{LCS of } X_{m-1} + Y = \text{pine}.$

## 8.2. Longest Common Sequence (LCS)

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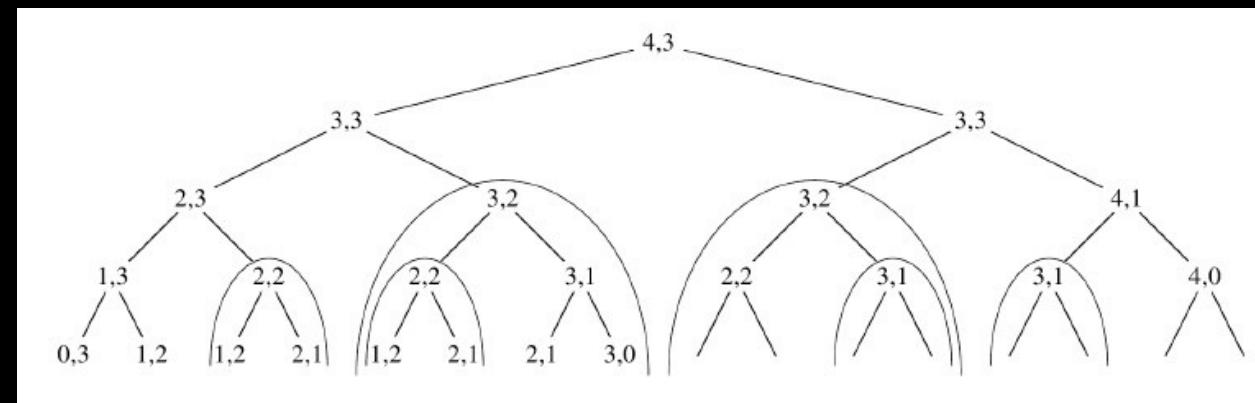


Recursive formulation:

- We define  $c[i, j]$  = **length** of LCS of  $X_i$  and  $Y_j$ .
- We want  $c[m, n]$ .

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

*new LCS is found*



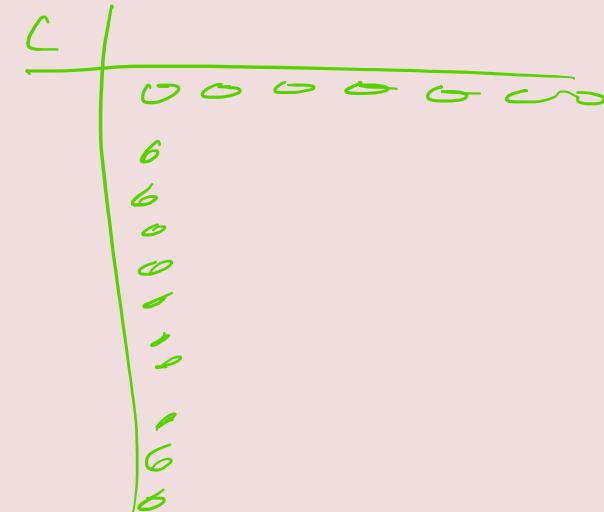
## 8.2. Longest Common Sequence (LCS)

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Algorithm (LCS-LENGTH(X, Y, m, n))

```
(1) let  $b[1 \dots m, 1 \dots n]$  and  $c[0 \dots m, 0 \dots n]$  be new tables track the position
(2) for  $(1 \leq i \leq m)$  do length of LCS
(3)    $c[i, 0] = 0$ 
(4)   for  $(1 \leq j \leq n)$  do
(5)      $c[0, j] = 0$ 
(6)   for  $(1 \leq i \leq m)$  do
(7)     for  $(1 \leq j \leq n)$  do
(8)       if  $(x_i == y_j)$  then
(9)          $c[i, j] = c[i - 1, j - 1] + 1$ 
(10)         $b[i, j] = \nwarrow$ 
(11)       else
(12)         if  $(c[i - 1, j] \geq c[i, j - 1])$  then
(13)            $c[i, j] = c[i - 1, j] \leftarrow \max$ 
(14)            $b[i, j] = \uparrow$ 
(15)         else
(16)            $c[i, j] = c[i, j - 1] \leftarrow \min$ 
(17)            $b[i, j] = \leftarrow$ 
(18)       fi
(19)   return  $c$  and  $b$ 
```



## 8.2. Longest Common Sequence (LCS)



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- Initial call is PRINT-LCS (b, X, m, n). ↪ Direction ↪ last Y ↪ Bottom-up.
- b[i, j] points to the table entry whose subproblem we used in solving the LCS of  $X_i$  and  $Y_j$ .
- When b[i, j]=↖, we have extended LCS by one character. So, the LCS=entries with ↖ in them.

```
Algorithm (PRINT-LCS(b, X, i, j))
1  if (i=0, j=0)  then
2      return
3  if (b[i, j]=↖)  then
4      PRINT-LCS (b, X, i-1, j-1)
5      print xi
6  else
7      if (b[i, j]=↑)  then
8          PRINT-LCS (b, X, i-1, j)
9      else
10         PRINT-LCS (b, X, i, j-1)
```

## 8.2. Longest Common Sequence (LCS)

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Example: LCS for spanking and amputation?



	A	M	P	U	T	A	T	I	O	N
	0	0	0	0	0	0	0	0	0	0
S	0	0	0	0	0	0	0	0	0	0
A	0	1	1	1	1	1	2	0	0	0
P	0	1	1	2	2	2	.	.	-	-
A	0	2	2	2	2	2	3			
N	0									
K	0									
I	0									
N	0									
G	0									

Algorithm (LCS-LENGTH(X, Y, m, n))

- (1) let  $b[1 \dots m, 1 \dots n]$  and  $c[0 \dots m, 0 \dots n]$  be new tables
- (2) for  $(1 \leq i \leq m)$  do
- (3)      $c[i, 0] = 0$
- (4) for  $(1 \leq j \leq n)$  do
- (5)      $c[0, j] = 0$

## 8.2. Longest Common Sequence (LCS)

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Example: Fill table  $c[0 \dots m, 0 \dots n]$



	A	M	P	U	T	A	T	I	O	N
0←	0←	0←	0←	0←	0←	0←	0←	0←	0←	0←
S	0←	0↑	0↑	0↑	0↑	0↑	0↑	0↑	0↑	0↑
P	0←	0←	0←	1↖	1←	1←	1←	1←	1←	1←
A	0←	1↑	1←	1↑	1↑	1↑	2↖	2↑	2↑	2↑
N	0←	1↑	1↑	1↑	1↑	1↑	2↑	2↑	2↑	3↖
K	0←	1↑	1↑	1↑	1↑	1↑	2↑	2↑	2↑	3↑
I	0←	1↑	1↑	1↑	1↑	1↑	2↑	2↑	3↖	3↑
N	0←	1↑	1↑	1↑	1↑	1↑	2↑	2←	3↑	4↖
G	0←	1↑	1↑	1↑	1↑	1↑	2↑	2↑	3↑	4↑

```

for (1 ≤ i ≤ m) do
  for (1 ≤ j ≤ n) do
    if ( $x_i == y_j$ ) then
       $c[i,j] = c[i - 1, j - 1] + 1$ 
       $b[i,j] = \nwarrow$ 
    else
      if ( $c[i - 1, j] ≥ c[i, j - 1]$ ) then
         $c[i,j] = c[i - 1, j]$ 
         $b[i,j] = \uparrow$ 
      else
         $c[i,j] = c[i, j - 1]$ 
         $b[i,j] = \leftarrow$ 
    fi
  
```

## 8.2. Longest Common Sequence (LCS)

BXJU2



	A	M	P	U	T	A	T	I	O	N
	0← 0←	0← 0←	0← 0←	0← 0←	0← 0←	0← 0←	0← 0←	0← 0←	0← 0←	0← 0←
S	0← 0↑	0↑ 0↑	0↑ 0↑	0↑ 0↑	0↑ 0↑	0↑ 0↑	0↑ 0↑	0↑ 0↑	0↑ 0↑	0↑ 0↑
P	0↑ 0←	0← 1↖	1↖ 1↖	1↖ 1↖	1↖ 1↖	1↖ 1↖	1↖ 1↖	1↖ 1↖	1↖ 1↖	1↖ 1↖
A	0↑ 1↖	1↖ 1↑	1↑ 1↑	1↑ 1↑	1↑ 2↖	2↖ 2↖	2↑ 2↑	2↑ 2↑	2↑ 2↑	2↑ 2↑
N	0← 1↑	1↑ 1↑	1↑ 1↑	1↑ 1↑	1↑ 2↑	2↑ 2↑	2↑ 2↑	2↑ 2↑	3↖ 3↖	
K	0← 1↑	1↑ 1↑	1↑ 1↑	1↑ 1↑	1↑ 2↑	2↑ 2↑	2↑ 2↑	2↑ 2↑	3↑ 3↑	
I	0← 1↑	1↑ 1↑	1↑ 1↑	1↑ 1↑	1↑ 2↑	2↑ 2↑	3↖ 3↖	3↖ 3↖	3↑ 3↑	
N	0← 1↑	1↑ 1↑	1↑ 1↑	1↑ 1↑	1↑ 2↑	2↑ 2↑	2↑ 3↑	3↑ 3↑	4↖ 4↖	
G	0← 1↑	1↑ 1↑	1↑ 1↑	1↑ 1↑	1↑ 2↑	2↑ 2↑	2↑ 3↑	3↑ 3↑	3↖ 4↑	

Algorithm (PRINT-LCS(b, X, i, j))

```

1  if (i=0, j=0) then
2      return
3  if (b[i,j]=↖) then
4      PRINT-LCS (b,X,i-1,j-1)
5      print xi
6  else
7      if (b[i,j]=↑) then
8          PRINT-LCS (b,X,i-1,j)
9      else
10         PRINT-LCS (b,X,i,j-1)

```

## 8.3. Sequence Alignment

BXJU2



- Dynamic programming algorithm that performs a **local sequence alignment**.
- Determines similar regions between two nucleotide or protein sequences.
- For us sequences are strings with 4 different characters.
- Sequence  $X = x_1, \dots, x_n$  (along table rows) and  $Y = y_1, \dots, y_m$  (along table columns) are given.

## 8.3. Sequence Alignment

BXJU2



- Sequence alignment is recursively defined as follows:

$$M(i, 0) = 0, \text{ for all } 0 \leq i \leq n$$

$$M(0, j) = 0, \text{ for all } 0 \leq j \leq m$$

$$M(i, j) = \max \begin{cases} M(i - 1, j - 1) + 2 & \text{if } x_i = y_j \\ M(i - 1, j - 1) - 1 & \text{if } x_i \neq y_j \\ M(i - 1, j) - 1 & \text{if } x_i \neq y_j, \text{ insert “-” into } Y \\ M(i, j - 1) - 1 & \text{if } x_i \neq y_j, \text{ insert “-” into } X \end{cases}$$

## 8.3. Sequence Alignment

BXJU2



- The matchings  $X'$  and  $Y'$  might contain “-” filter characters.
- $X'$  (or  $Y'$ ) might not contain all characters out of  $X$  (or  $Y$ ).

	Example 1	Example 2	Example 3
X	abababda	cacacccbab	cdbaabbdcda
$X'$	a-bababda	ca-cacccbab	c-dba--abbdca
$Y'$	acbaba-b-a	cadaadcc---	cadcacca-bd--
Y	acbaba-ba	bccadaadcc	cadcaccabd
$M(n,m)$	12	4	5

	Example 4	Example 5
X	caacbdacca	dcacccbbba
$X'$	caacb-dacc-a	dcacccb-bba
$Y'$	c--cbcd-ccba	dca---badba
Y	bccbcdccba	aadcabadba
$M(n,m)$	9	7

## 8.3. Sequence Alignment

BXJU2



Algorithm (SMITH-WATERMAN(X, Y))

```
1 New Tables: H[0...n, 0...m], P[0...n, 0...m]
2 for (0≤i≤n) do
3     H[i][0]=P[i][0]=0
4 for (0≤j≤m) do
5     H[0][j]=P[0][j]=0
6 for (1≤i≤n) do
7     for (1≤j≤m) do
8         if (Xi=Yj) then
9             P1 = H[i-1][j-1]+2
10        else
11            P1 = H[i-1][j-1]-1
12            P2 = H[i-1][j]-1
13            P3 = H[i][j-1]-1
14            H[i][j] = max{P1, P2, P3}
```

SMITH-WATERMAN(X, Y) continue...

```
14     H[i][j] = max{P1, P2, P3}
15     if (H[i][j] = p1) then
16         P[i][j] = ↗
17     else
18         if (H[i][j] = p2) then
19             P[i][j] = ↑
20         else
21             P[i][j] = ←
22 return (H, P)
```

P<sub>3</sub>

## 8.3. Sequence Alignment

BXJU2



Algorithm (PRINT-SEQ-ALIGN-X( $X, P, n, m$ ))

```
1 if ( $P[n][m] = \nwarrow$ ) then
2     PRINT-SEQ-ALIGN-X( $X, P, n-1, m-1$ )
3     print  $X_n$ 
4 else
5     if ( $P[n][m] = \leftarrow$ ) then
6         PRINT-SEQ-ALIGN-X( $X, P, n, m-1$ )
7         print  $X_n$ 
8     else
9         PRINT-SEQ-ALIGN-X( $X, P, n-1, m$ )
10    print -
```

- The algorithm PRINT-SEQ-ALIGN-Y( $Y, P, n, m$ ) is symmetric to PRINT-SEQ-ALIGN-X.
- PRINT-SEQ-ALIGN-Y outputs the matching sequence  $Y'$  for  $Y$  instead of the matching sequence  $X'$  for  $X$ .

## 8.3. Sequence Alignment

BXJU2



	-	a	b	a	b	a	b	d	a
-	0	0	0	0	0	0	0	0	0
a	0								
c	0								
b	0								
a	0								
b	0								
a	0								
b	0								
a	0								

Algorithm (SMITH-WATERMAN(X, Y))

```
2  for (0≤i≤n) do
3      H[i][0]=P[i][0]=0
4  for (0≤j≤m) do
5      H[0][j]=P[0][j]=0
```

## 8.3. Sequence Alignment

BXJU2



	-	a	b	a	b	a	b	d	a
-	0	0	0	0	0	0	0	0	0
a	0	2	1	2	1	2	1	0	2
c	0	1	1	1	1	1	1	0	1
b	0	0	3	2	3	2	3	2	1
a	0	2	2	5	4	5	4	3	4
b	0	1	4	4	7	6	7	6	5
a	0	2	3	6	6	9	8	7	8
b	0	1	4	5	8	8	11	10	9
a	0	2	3	6	7	10	10	10	12

Algorithm (SMITH-WATERMAN(X, Y))

```

6   for (1≤i≤n) do
7       for (1≤j≤m) do
8           if (Xi=Yj) then
9               P1 = H[i-1][j-1]+2
10      else
11          P1 = H[i-1][j-1]-1
12          P2 = H[i-1][j]-1
13          P3 = H[i][j-1]-1
14          H[i][j] = max{P1,P2,P3}
```

## 8.3. Sequence Alignment

BXJU2



	-	a	b	a	b	a	b	d	a
-	0	0	0	0	0	0	0	0	0
a	0	2↖	1↑	2↖	1↑	2↖	1↑	0↑	2↖
c	0	1←	1↖	1←	1↖	1←	1↖	0↖	1←
b	0	0←	3↖	2↑	3↖	2↑	3↖	2↑	1↑
a	0	2↖	2←	5↖	4↑	5↖	4↑	3↑	4↖
b	0	1←	4↖	4←	7↖	6↑	7↖	6↑	5↑
a	0	2↖	3←	6↖	6←	9↖	8↑	7↑	8↖
b	0	1←	4↖	5←	8↖	8←	11↖	10↑	9↑
a	0	2↖	3←	6↖	7←	10↖	10←	10↖	12↖

SMITH-WATERMAN(X, Y) continue...

```

14         H[i][j] = max{p1, p2, p3}
15         if (H[i][j] = p1) then
16             P[i][j] = ↖
17         else
18             if (H[i][j] = p2) then
19                 P[i][j] = ↑
20             else
21                 P[i][j] = ←
22     return (H, P)

```

# 8.3. Sequence Alignment

BXJU2



	-	a	b	a	b	a	b	d	a
-	0	0	0	0	0	0	0	0	0
a	0	2↖	1↑	2↖	1↑	2↖	1↑	0↑	2↖
c	0	1←	1↖	1←	1↖	1←	1↖	0↖	1←
b	0	0←	3↖	2↑	3↖	2↑	3↖	2↑	1↑
a	0	2↖	2←	5↖	4↑	5↖	4↑	3↑	4↖
b	0	1←	4↖	4←	7↖	6↑	7↖	6↑	5↑
a	0	2↖	3←	6↖	6←	9↖	8↑	7↑	8↖
b	0	1←	4↖	5←	8↖	8←	11↖	10↑	9↑
a	0	2↖	3←	6↖	7←	10↖	10←	10↖	12↖

Algorithm (PRINT-SEQ-ALIGN-X(X, P, n, m))

```

1  if (P[n][m]=↖) then
2      PRINT-SEQ-ALIGN-X(X,P,n-1,m-1)
3      print Xn
4  else
5      if (P[n][m]=←) then
6          PRINT-SEQ-ALIGN-X(X,P,n,m-1)
7          print Xn
8      else
9          PRINT-SEQ-ALIGN-X(X,P,n-1,m)
10     print -

```

PRINT-SEQ-ALIGN-X(X, P, n, m) prints

- $X' = \text{acbaba}-\text{a}$

PRINT-SEQ-ALIGN-Y(Y, P, n, m) prints

- We print - if  $P[i][j]=\leftarrow$  and print  $Y_n$  if  $P[i][j]=\uparrow$ .
- $Y' = \text{a}-\text{bababda}$

## 8.3. Optimal Binary Search Trees

BXJU2



- We are given a sequence  $K = [k_1, \dots, k_n]$  of  $n$  distinct keys, sorted ( $k_1 < \dots < k_n$ ).
- We want to build a BST from the keys.
- For each key  $k_i$ , we have **probability  $p_i$**  that a search is for  $k_i$ .
- We want a BST with **minimum expected search cost**.
- The actual cost is = number of items examined.

$$E[\text{search cost in } T] = \sum_{i=1}^n (d_T(k_i) + 1) \cdot p_i = 1 + \sum_{i=1}^n d_T(k_i) \cdot p_i$$

↑  
Depth

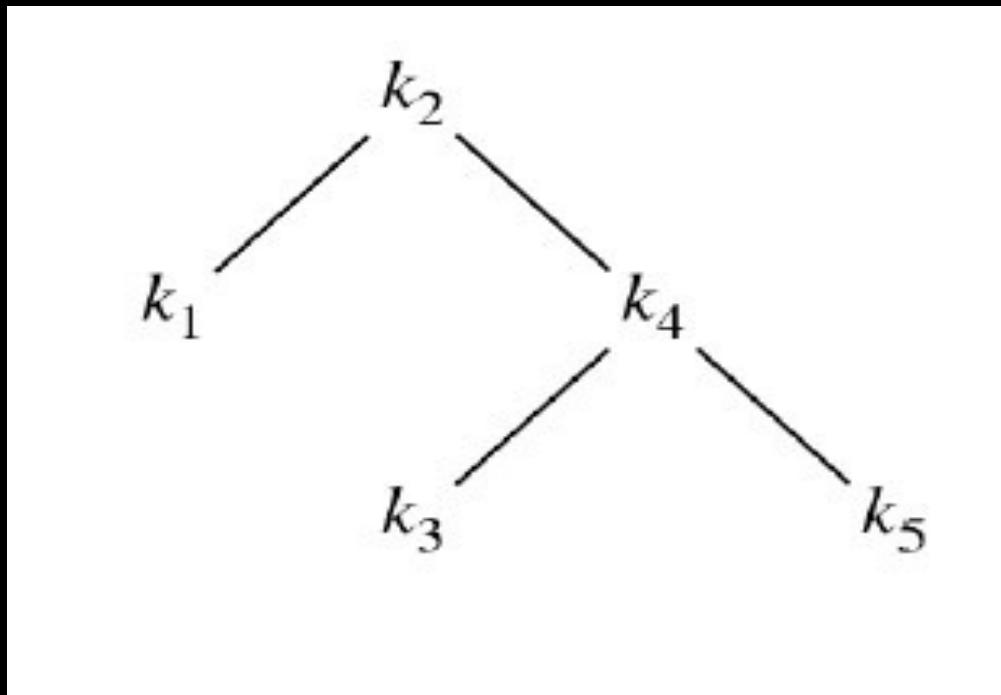
A red arrow points upwards from the word "Depth" to the term  $d_T(k_i)$  in the equation, indicating that the depth of a node in the tree is being calculated.

## 8.3. Optimal Binary Search Trees



$i$	1	2	3	4	5
$p_i$	0.25	0.2	0.05	0.2	0.3

$$E[\text{search cost in } T] = \sum_{i=1}^n d_T(k_i) \cdot p_i + 1$$



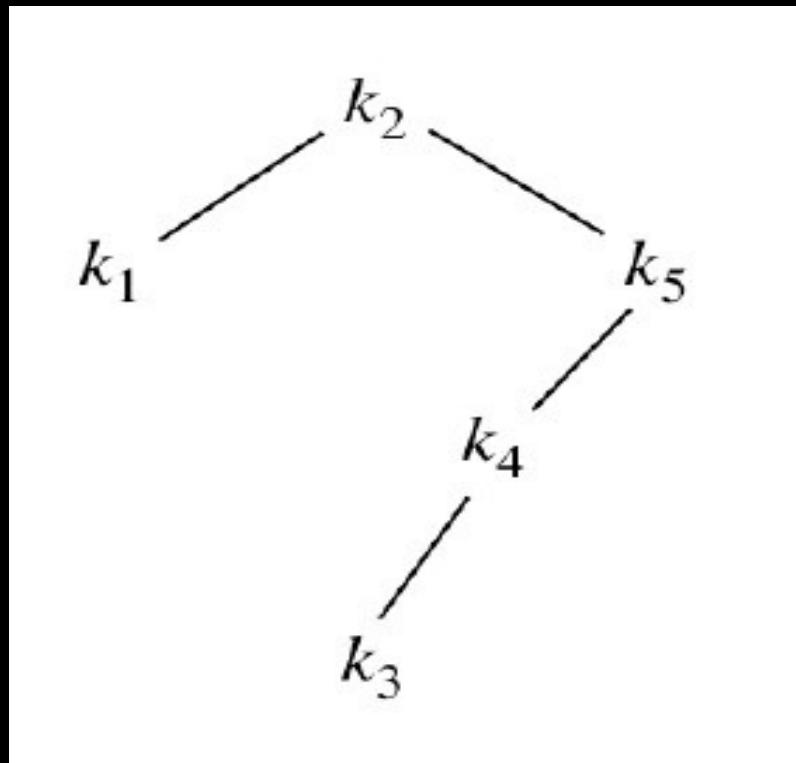
$i$	$d_T(k_i)$	$d_T(k_i) \cdot p_i$
1	1	0.25
2	0	0
3	2	0.1
4	1	0.2
5	2	0.6
$\sum d_T(k_i) \cdot p_i$		1.15
$E =$		2.15

## 8.3. Optimal Binary Search Trees



$i$	1	2	3	4	5
$p_i$	0.25	0.2	0.05	0.2	0.3

$$E[\text{search cost in } T] = \sum_{i=1}^n d_T(k_i) \cdot p_i$$



$i$	$d_T(k_i)$	$d_T(k_i) \cdot p_i$
1	1	0.25
2	0	0
3	3	0.15
4	2	0.4
5	1	0.3
$\sum d_T(k_i) \cdot p_i$		1.10
$E =$		2.10

## 8.3. Optimal Binary Search Trees

BXJU2



Observation:

- The optimal BST might not have the smallest height.
- The optimal BST might not have the key with the highest probability at the root.

Build by exhaustive checking?

1. We construct each n-node BST.
2. We then put in the keys for each of the BST's.
3. We then compute the expected search cost.

Problem:

- There are  $\Omega\left(\frac{4^n}{n^{\frac{3}{2}}}\right)$  different BST's with n nodes.

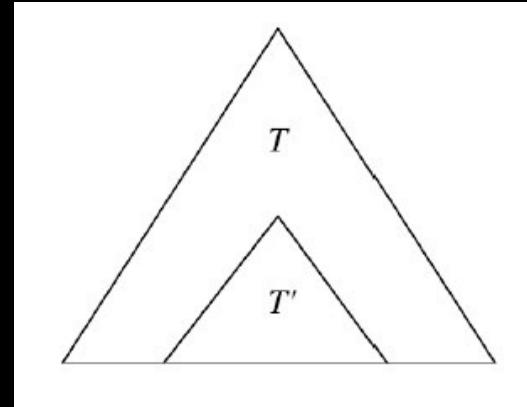
## 8.3. Optimal Binary Search Trees

BXJU2



Optimal substructure:

- We consider any subtree of a BST. It contains keys in a contiguous range  $k_i, \dots, k_j$ , for some  $1 \leq i \leq j \leq n$ .



- If the BST T is an optimal BST and T contains the subtree T' with keys  $k_i, \dots, k_j$ , then T' must be an optimal BST for keys  $k_i, \dots, k_j$ .

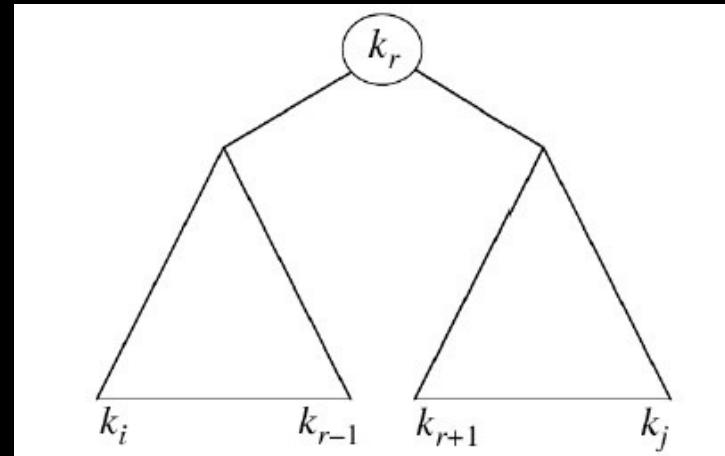
## 8.3. Optimal Binary Search Trees

BXJU2



Solution:

- We use the optimal substructure to construct an optimal solution to the problem from optimal solutions to subproblem.



$$K = [k_i \dots k_r \dots k_j]$$

$k_i \dots k_{r-1}$        $k_{r+1} \dots k_j$

left subtree                  right subtree.

if  $T.\text{root} = k_r$  is optimize,  
 $\text{left}.T + \text{right}.T$  are optimize.

- If the BST  $T$  is an optimal BST and  $T$  contains the subtree  $T'$  with keys  $k_i, \dots, k_j$ , then  $T'$  must be an optimal BST for keys  $k_i, \dots, k_j$ .

## 8.3. Optimal Binary Search Trees

BXJU2

Solution (continued)

- We are guaranteed to find an optimal BST for  $k_i, \dots, k_j$  if the following two conditions are satisfied.
  - We examine all candidate roots  $k_r$  for  $i \leq r \leq j$ .
  - We determine all optimal BST's containing  $k_i, \dots, k_{r-1}$  (left subtree) and containing  $k_{r+1}, \dots, k_j$  (right subtree).



## 8.3. Optimal Binary Search Trees

BXJU2



### Recursive Solution:

- Subproblem domain:
  - Find an optimal BST for  $k_i, \dots, k_j$ , where  $i \geq 1, j \leq n$ , and  $j \geq i - 1$ .
  - The tree is empty when  $j = i - 1$ .
- We define  $e[i, j] =$  expected search cost of the optimal BST for  $k_i, \dots, k_j$ .  
\* cost table
- If  $j = i - 1$ , then  $e[i, j] = 0$ .
- If  $j \geq i$ ,
  - We select a root  $k_r$ , for some  $i \leq r \leq j$ .
  - We make an optimal BST with  $k_i, \dots, k_{r-1}$  as left subtree.
  - We make an optimal BST with  $k_{r+1}, \dots, k_j$  as right subtree.
  - Note: if  $r = i$ , the left subtree is  $k_i, \dots, k_{i-1}$ . Similar for  $r = j$ . The right subtree is  $k_{j+1}, \dots, k_j$ .

## 8.3. Optimal Binary Search Trees

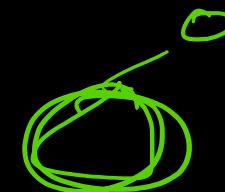
BXJU2



Recursive Solution (continue):

- When a subtree becomes a subtree of a node:
  - The depth of every node in the subtree increases by 1.
  - The expected search cost increases by

$$w(i, j) = \sum_{l=i}^j p_l .$$



- If  $k_r$  is the root of an optimal BST for  $k_i, \dots, k_j$ :

$$e[i, j] = p_r + e[i, r - 1] + w(i, r - 1) + e[r + 1, j] + w(r + 1, j).$$

A diagram illustrating the recursive formula. It shows the equation  $e[i, j] = p_r + e[i, r - 1] + w(i, r - 1) + e[r + 1, j] + w(r + 1, j)$ . A green arrow points from the first term  $p_r$  to the label 'Root'. Red brackets group the remaining terms into three parts: 'Left subtree' (covering  $e[i, r - 1]$  and  $w(i, r - 1)$ ) and 'Right subtree' (covering  $e[r + 1, j]$  and  $w(r + 1, j)$ ).

## 8.3. Optimal Binary Search Trees

BXJU2



Recursive Solution (continue):

- But we have

$$w(i, j) = \underbrace{w(i, r - 1)}_{\text{left depth inner}} + \underbrace{p_r}_{\text{root}} + \underbrace{w(r + 1, j)}_{\text{right depth inner}}.$$

Eq. 8-1

- Therefore, we get

$$e[i, j] = e[i, r - 1] + e[r + 1, j] + w(i, j).$$

- This assumes that we already known which of the keys we use as  $k_r$ .
- We need to try all possible candidates, and pick the best one:

$$e[i, j] = \begin{cases} 0 & \text{if } j = i - 1 \\ \min_{i \leq r \leq j} \{e[i, r - 1] + e[r + 1, j] + w(i, j)\} & \text{if } i \leq j \end{cases}$$

Eq. 8-2

## 8.3. Optimal Binary Search Trees

BXJU2



### Computing an optimal solution

- We will store the values in a table as we did before,  $e[1 \dots n + 1, 0 \dots n]$  can store  $e[n + 1, n]$  and  $e[1, 0]$ .
  - We will use only entries  $e[i, j]$ , where  $j \geq i - 1$ .
  - We will also compute  $R[i, j] =$ root of the subtree with keys  $k_i, \dots, k_j$ , for  $1 \leq i \leq j \leq n$ .
- We need  $w[1 \dots n + 1, 0 \dots n]$  table to avoid  $w(i, j)$  re-computation: there will be additional  $\Theta(j - i)$  each time.
  - $w[i, i - 1] = 0$  for  $1 \leq i \leq n$ .
  - $w[i, j] = w[i, j - 1] + p_j$  for  $1 \leq i \leq j \leq n$ .
  - Computes all  $\Theta(n^2)$  values in  $O(1)$  time each.

## 8.3. Optimal Binary Search Trees

BXJU2



### Algorithm

- We have a first for-loop that initialize the entries in  $e$  and  $w$  for subtrees with 0 keys.
- We have a main for-loop that:
  - The iterations for  $l$  works on subtrees with  $l$  keys.
  - Idea: we compute in the order of the subtree sizes, smaller (1 key) to larger ( $n$  keys).

## 8.3. Optimal Binary Search Trees

BXJU2

### Algorithm

Algorithm (OPTIMAL-BST( $p, q, n$ ))

```
1  e[1...n+1, 0...n], w[1...n+1, 0...n], R[1...n, 1...n]
2  for ( $i \leq i \leq n+1$ ) do
3      e[i, i-1] = 0, w[i, i-1] = 0
4  for ( $1 \leq l \leq n$ ) do ← entire ↲
5      for ( $1 \leq i \leq n-l+1$ ) do
6          j = i+l-1
7          e[i, j] =  $\infty$  ← why? we are looking for min value.
8          w[i, j] = w[i, j-1] + p_j           //Eq. 8-1
9          for ( $i \leq r \leq j$ ) do             ← temporary cost.
10         t = e[i, r-1] + e[r+1, j] + w[i, j] //Eq. 8-2
11         if (t < e[i, j]) then
12             R[i, j] = r ← storing the root of subtree.
13 return e and root
```



## 8.3. Optimal Binary Search Trees

BXJU2



$i$	1	2	3	4	5
$p_i$	0.25	0.2	0.05	0.2	0.3

```
2  for (i≤i≤n+1) do
3      e[i,i-1]=0, w[i,i-1]=0
```

$e$	0	1	2	3	4	5
1	0					
2	0					
3	0					
4	0					
5	0					
6	0					

$w$	0	1	2	3	4	5
1	0					
2	0					
3	0					
4	0					
5	0					
6	0					

$R$	1	2	3	4	5
1	1				
2	2				
3		3			
4			4		
5				5	

$$j \geq i - 1$$

## 8.3. Optimal Binary Search Trees



BXJU2

$i$	1	2	3	4	5
$p_i$	0.25	0.2	0.05	0.2	0.3

```

4   for (1≤l≤n) do
5     for (1≤i≤n-1+1) do
6       j = i+1-1
7       e[i,j] = ∞
8       w[i,j] = w[i,j-1]+pj
9       for (i≤r≤j) do
10         t = e[i,r-1]+e[r+1,j]+w[i,j]
11         if (t < e[i,j]) then
12           R[i,j] = r

```

$w$	0	1	2	3	4	5
1	0	0.25				
2		0	0.2			
3			0	0.05		
4				0	0.2	
5					0	0.3
6						0

$R$	1	2	3	4	5
1	1				
2		2			
3			3		
4				4	
5					5

$e$	0	1	2	3	4	5
1	0	0.25				
2		0	0.2			
3			0	0.05		
4				0	0.2	
5					0	0.3
6						0

## 8.3. Optimal Binary Search Trees

BXJU2



$i$	1	2	3	4	5
$p_i$	0.25	0.2	0.05	0.2	0.3

```

4   for (1≤i≤n) do
5     for (1≤i≤n-1+1) do
6       j = i+1-1
7       e[i,j] = ∞
8       w[i,j] = w[i,j-1]+pj
9       for (i≤r≤j) do
10      t = e[i,r-1]+e[r+1,j]+w[i,j]
11      if (t < e[i,j]) then
12        R[i,j] = r

```

$w$	0	1	2	3	4	5
1	0	0.25	0.45			
2		0	0.2			
3			0	0.05		
4				0	0.2	
5					0	0.3
6						0

For  $i=1, j=2$ :

- $w[1,2]=w[1,1]+p_2=0.25+0.2=0.45$
- $r=1: e[1,2]=e[1,0]+e[2,2]+w[1,2]=0+0.2+0.45$
- $r=2: e[1,2]=e[1,1]+e[3,2]+w[1,2]=0.25+0+0.45$

$e$	0	1	2	3	4	5	$R$	1	2	3	4	5
1	0	0.25	0.65				1	1	1			
2			0	0.2			2		2			
3				0	0.05		3			3		
4					0	0.2	4				4	
5						0	0.3	5				5
6							0					

## 8.3. Optimal Binary Search Trees

BXJU2



$i$	1	2	3	4	5
$p_i$	0.25	0.2	0.05	0.2	0.3

```

4   for (1≤i≤n) do
5     for (1≤i≤n-1+1) do
6       j = i+1-1
7       e[i,j] = ∞
8       w[i,j] = w[i,j-1]+pj
9       for (i≤r≤j) do
10      t = e[i,r-1]+e[r+1,j]+w[i,j]
11      if (t < e[i,j]) then
12        R[i,j] = r

```

$w$	0	1	2	3	4	5
1	0	0.25	0.45			
2		0	0.2	0.25		
3			0	0.05		
4				0	0.2	
5					0	0.3
6						0

For  $i=2, j=3$ :

- $w[2,3]=w[2,2]+p_3=0.2+0.05=0.25$
- $r=2: e[2,3]=e[2,1]+e[3,3]+w[2,3]=0+0.05+0.25$
- $r=3: e[2,3]=e[2,2]+e[4,3]+w[2,3]=0.2+0+0.25$

$e$	0	1	2	3	4	5	$R$	1	2	3	4	5
1	0	0.25	0.65				1	1	1			
2			0	0.2	0.3		2	2	2			
3				0	0.05		3		3			
4					0	0.2	4			4		
5						0	0.3				5	
6							0					5

## 8.3. Optimal Binary Search Trees

BXJU2



$i$	1	2	3	4	5
$p_i$	0.25	0.2	0.05	0.2	0.3

```

4   for (1≤i≤n) do
5     for (1≤i≤n-1+1) do
6       j = i+1-1
7       e[i,j] = ∞
8       w[i,j] = w[i,j-1]+pj
9       for (i≤r≤j) do
10      t = e[i,r-1]+e[r+1,j]+w[i,j]
11      if (t < e[i,j]) then
12        R[i,j] = r

```

$w$	0	1	2	3	4	5
1	0	0.25	0.45	0.5		
2		0	0.2	0.25		
3			0	0.05		
4				0	0.2	
5				0	0.3	
6					0	

For  $i=1, j=3$ :

- $w[1,3]=w[1,2]+p_3=0.42+0.05=0.5$
- $r=1: e[1,3]=e[1,0]+e[2,3]+w[1,3]=0+0.3+0.5$
- $r=2: e[1,3]=e[1,1]+e[3,3]+w[1,3]=0.25+0.05+0.5$
- $r=3: e[1,3]=e[1,2]+e[4,3]+w[1,3]=0.65+0+0.5$

$e$	0	1	2	3	4	5	$R$	1	2	3	4	5
1	0	0.25	0.65	0.8			1	1	1	1		
2		0	0.2	0.3			2	2	2			
3			0	0.05			3			3		
4				0	0.2		4				4	
5					0	0.3	5					5
6						0						



## 8.3. Optimal Binary Search Trees

BXJU2

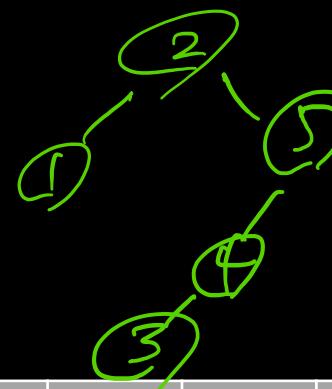


$i$	1	2	3	4	5
$p_i$	0.25	0.2	0.05	0.2	0.3

$w$	0	1	2	3	4	5
1	0	0.25	0.45	0.5	0.7	1.0
2		0	0.2	0.25	0.45	0.75
3			0	0.05	0.25	0.55
4				0	0.2	0.5
5					0	0.3
6						0

$e$	0	1	2	3	4	5
1	0	0.25	0.65	0.8	1.25	2.10
2		0	0.2	0.3	0.75	1.35
3			0	0.05	0.3	0.85
4				0	0.2	0.7
5					0	0.3
6						0

$R$	1	2	3	4	5
1	1	1	1	2	2
2		2	2	2	4
3			3	4	5
4				4	5
5					5



## 8.3. Optimal Binary Search Trees

BXJU2



### Time:

- We have 3 (deep) nested for loop, each loop index takes values  $\leq n \Rightarrow O(n^3)$ .
- We can also show  $\Omega(n^3) \Rightarrow \Theta(n^3)$ .

## 8.3. Optimal Binary Search Trees

BXJU2

### Construct an optimal solution

Algorithm (CONSTRUCT-OPTIMAL-BST(R))

```
1 r = R[1,n]
2 print r "is the root"
3 CONSTRUCT-OPT-SUBTREE (1,r-1,r,"left",R)
4 CONSTRUCT-OPT-SUBTREE (r+1,n,r,"right",R)
```

Algorithm (CONSTRUCT-OPT-SUBTREE(i,j,r,dir,R))

```
1 if (i ≤ j) then
2     t = R[i,j]
3     print t "is " dir "child of" r
4     CONSTRUCT-OPT-SUBTREE (1,t-1,t,"left",R)
5     CONSTRUCT-OPT-SUBTREE (t+1,j,t,"right",R)
```



## 8.3. Optimal Binary Search Trees

Construct an optimal solution

Algorithm (CONSTRUCT-OPTIMAL-BST(R))

```
1 r = R[1,n]
2 print r "is the root"
3 CONSTRUCT-OPT-SUBTREE (1,r-1,r,"left",R)
4 CONSTRUCT-OPT-SUBTREE (r+1,n,r,"right",R)
```

Algorithm (CONSTRUCT-OPT-SUBTREE(i,j,r,dir,R))

```
1 if (i ≤ j) then
2     t = R[i,j]
3     print t "is " dir "child of" r
4     CONSTRUCT-OPT-SUBTREE (1,t-1,t,"left",R)
5     CONSTRUCT-OPT-SUBTREE (t+1,j,t,"right",R)
```

BXILJ2

R	1	2	3	4	5
1	1	1	1	2	2
2		2	2	2	4
3			3	4	5
4				4	5
5					5

2 is the root  
1 is left child of 2  
5 is right child of 2  
4 is left child of 5  
3 is left child of 4