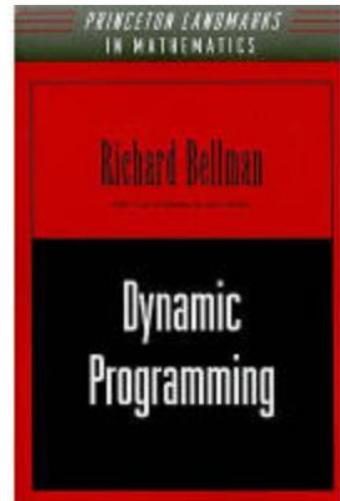


15 Dynamic Programming

15 Dynamic Programming



Richard Bellman.
Dynamic Programming.
Princeton University
Press, 1957.

¥411.00

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dynamic programming

文章

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Dynamic programming

R Bellman - Science, 1966 - science.sciencemag.org

Little has been done in the study of these intriguing questions, and I do not wish to give the impression that any extensive set of ideas exists that could be called a "theory." What is quite surprising, as far as the histories of science and philosophy are concerned, is that the major impetus for the fantastic growth of interest in brain processes, both psychological and ...

☆ 囗 被引用次数: 26841 相关文章 所有 50 个版本 ≫

15 Dynamic Programming

- ✓ Scheduling two automobile assembly lines
- ✓ Steel rod cutting (15.1)
- ✓ **Matrix-chain multiplication (15.2)**
矩阵链相乘，或矩阵连乘问题
- ✓ Characteristics(Elements) of dynamic programming (15.3)
- ✓ Longest common subsequence (15.4)
- ✓ **Optimal binary search trees (15.5)**

15.2 Matrix-chain multiplication (MCM)

- Given a sequence (chain) $\langle A_1, A_2, \dots, A_n \rangle$ of n matrices to be multiplied, and we wish to compute the product n 个矩阵相乘，称为‘矩阵连乘’，如何求积？

$$A_1 A_2 A_3 A_4 \quad (15.10)$$

$$(A_1 (A_2 (A_3 A_4))), (A_1 ((A_2 A_3) A_4)), ((A_1 A_2) (A_3 A_4)), \dots$$

- We can evaluate (15.10) using the standard algorithm for multiplying pairs of matrices as a subroutine once we have parenthesized it.
- A product of matrices is fully parenthesized if it is either a single matrix or the product of two fully parenthesized matrix products, surrounded by parentheses. Example, $A_1, (A_1((A_2 A_3) A_4)), (A_1((A_2 A_3)(A_4 A_5)))$.

矩阵连乘全括号：仅有一个矩阵，或者两个“矩阵连乘全括号”的乘积且外层包括一个括号，如： $(\underline{A_1} (\underline{\underline{A_2 A_3}}) \underline{A_4})$

这是嵌套的矩阵对，它给出了矩阵连乘的一种求解顺序，也简称“矩阵全括号”。

Example: Multiplication of two matrices (矩阵相乘)

two $n \times n$ matrices A and B, Complexity($C = A \times B$) = ?

Standard method

$$c_{ij} = \sum_{k=1}^n a_{ik} b_{kj}$$

$$\begin{pmatrix} \dots & \dots \\ \dots & c_{ij} & \dots \\ \dots & \dots \\ \dots & \dots \end{pmatrix} = \begin{pmatrix} \dots & \dots \\ \#\# & \dots & \# \\ \dots & \dots \\ \dots & \dots \end{pmatrix} * \begin{pmatrix} \dots & \# \dots \\ \dots & \# \dots \\ \dots & \dots \\ \dots & \# \dots \end{pmatrix}$$

MATRIX-MULTIPLY(A, B)

for $i \leftarrow 1$ to n

 for $j \leftarrow 1$ to n

$C[i, j] \leftarrow 0$

 for $k \leftarrow 1$ to n

$C[i, j] \leftarrow C[i, j] + A[i, k] \cdot B[k, j]$

return C

Complexity:
 $O(n^3)$ multiplications
and additions.
 $T(n) = O(n^3)$.

15.2 Matrix-chain multiplication

- Given a sequence (chain) $\langle A_1, A_2, \dots, A_n \rangle$ of n matrices to be multiplied, and we wish to compute the product

$$A_1 A_2 A_3 A_4. \quad (15.10)$$

- Matrix multiplication is **associative**, so all parenthesizations yield the **same product**. For example, if the chain of matrices is $\langle A_1, A_2, A_3, A_4 \rangle$, the product $A_1 A_2 A_3 A_4$ can be fully parenthesized in five distinct ways:
矩阵连乘满足结合律，因此对所有加括号的方式，矩阵连乘的积相同。例如...

$$(A_1 (A_2 (A_3 A_4))), \quad (A_1 ((A_2 A_3) A_4)), \quad ((A_1 A_2) (A_3 A_4)), \\ ((A_1 (A_2 A_3)) A_4), \quad (((A_1 A_2) A_3) A_4).$$

15.2 Matrix-chain multiplication

The way we **parenthesize** a chain of matrices can have a dramatic impact on the cost of evaluating the product.

采用不同的加括号方式，可导致差异极大的乘法开销

$$(A_1 (A_2 (A_3 A_4))) ,$$

$$(A_1 ((A_2 A_3) A_4)) ,$$

$$((A_1 A_2) (A_3 A_4)) ,$$

$$((A_1 (A_2 A_3)) A_4) ,$$

$$(((A_1 A_2) A_3) A_4) .$$

15.2 Matrix-chain multiplication

- First, consider the cost of multiplying two matrices.
- Two matrices A and B can be multiplied only if they are compatible:
columns of A = rows of B . (仅当矩阵A和B相容时, A和B能相乘)
 - ◆ If A is $p \times q$, B is $q \times r$, then C is $p \times r$.
 - ◆ The time to compute C is dominated by the number of scalar multiplications in line 7, which is pqr .

$A * B \rightarrow C$

$$\begin{pmatrix} \dots \\ \# \dots \# \\ \dots \\ \dots \end{pmatrix}_{p^*q} * \begin{pmatrix} \dots \# \dots \\ \dots \# \dots \\ \dots \\ \dots \# \dots \end{pmatrix}_{q^*r} \Rightarrow \begin{pmatrix} \dots \dots \dots \\ \dots \dots c_{ij} \dots \\ \dots \\ \dots \end{pmatrix}_{p^*r}$$

MATRIX-MULTIPLY(A, B)

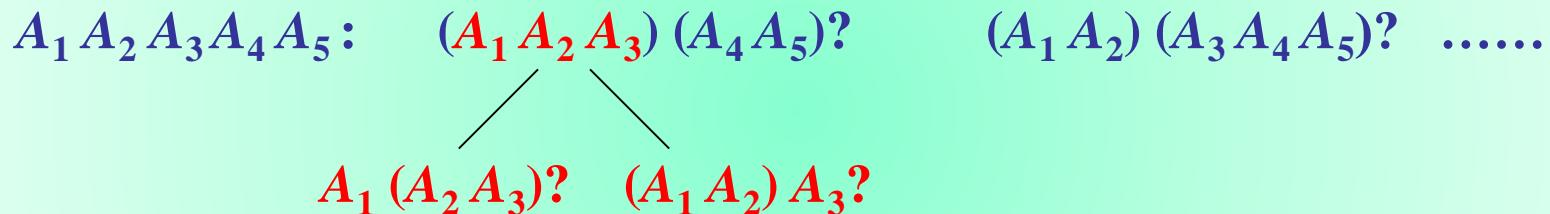
```
1 if columns[A] ≠ rows[B]
2   then return “error: incompatible dimensions”
3 else for i ← 1 to rows[A]    // p is row[A]
4       for j ← 1 to columns[B] // r is columns[B]
5           C[i,j] ← 0
6           for k ← 1 to columns[A] // q is columns[A]
7               C[i,j]←C[i,j]+A[i,k]·B[k,j]
8 return C
```

15.2 Matrix-chain multiplication

- For $A_{p \times q}, B_{q \times r}, C=AB$ is $p \times r$. The # of scalar multiplications is pqr .
- Consider the problem of a chain $\langle A_1, A_2, A_3 \rangle$,
Suppose that $A_1: 10 \times 100; A_2: 100 \times 5; A_3: 5 \times 50$
 - ◆ If $A = ((A_1 A_2) A_3)$,
 - a) $C = A_1 A_2$, # of multiplications $10 \cdot 100 \cdot 5 = 5000$, $C_{10 \times 5}$
 - b) $A = C A_3$, # of multiplications $10 \cdot 5 \cdot 50 = 2500$, $A_{10 \times 50}$
then, # of scalar multiplications, for a total of **7500**.
 - ◆ If $A = (A_1 (A_2 A_3))$,
 - a) $C_{100 \times 50} = A_2 A_3$, # of multiplications $100 \cdot 5 \cdot 50 = 25,000$,
 - b) $A_{10 \times 50} = A_1 C$, # of multiplications $10 \cdot 100 \cdot 50 = 50,000$,
then, # of scalar multiplications, for a total of **75,000** .
 - ◆ The first case is **10 times faster** than the second.

7,500 << 75,000

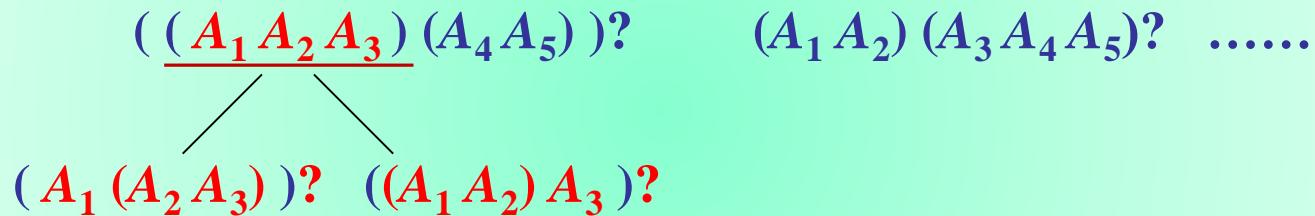
15.2 Matrix-chain multiplication



- **Matrix-chain multiplication problem :** Given a chain $\langle A_1, A_2, \dots, A_n \rangle$, $i=1, 2, \dots, n$, matrix A_i has dimension $p_{i-1} \times p_i$, fully parenthesize the product $A_1 A_2 \dots A_n$ in a way that minimizes the number of scalar multiplications.
- In the problem, we are not actually multiplying matrices. Our goal is only **to determine an order** for multiplying matrices that has the lowest cost.

Counting the number of parenthesizations

$A_1 A_2 A_3 A_4 A_5$

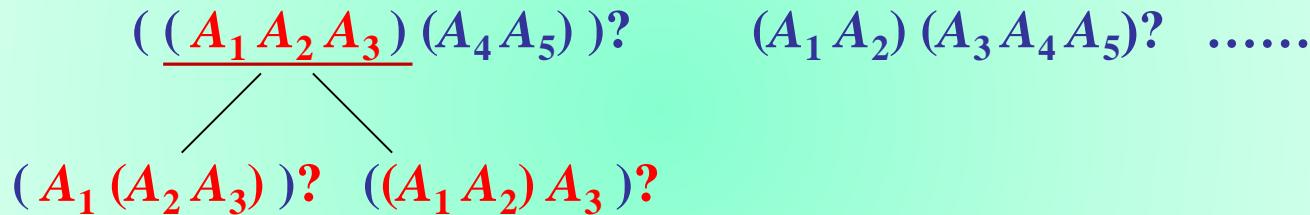


$$(\underbrace{(A_i (A_{i+1} \dots) (\dots) \dots A_k)}_{\text{one way}}) \underbrace{(A_{k+1} \dots A_{j-1} A_j)}_{\text{other ways}}$$

- Brute force, exhaustively checking all possible parenthesizations.
- $P(n)$: the # of alternative parenthesizations of n matrices. $P(n)$ 种全括号方式
 - $n=1$, one matrix, one way to parenthesize the matrix product.
 - $n \geq 2$,
- $$P(n) = \begin{cases} 1 & , \quad \text{if } n = 1, \\ \sum_{k=1}^{n-1} P(k)P(n-k), & \text{if } n \geq 2. \end{cases} \quad (15.11)$$
- The solution to (15.11) is $\Omega(2^n)$ (guess, then prove), a poor strategy.

Counting the number of parenthesizations

$A_1 A_2 A_3 A_4 A_5$



$((\underline{A_i} (\underline{A_{i+1} \dots}) (\dots) \dots A_k) (\underline{A_{k+1} \dots} \underline{A_{j-1} A_j}))$

$$P(n) = \begin{cases} 1 & , \text{if } n = 1, \\ \sum_{k=1}^{n-1} P(k)P(n-k), & \text{if } n \geq 2. \end{cases} \quad (15.11)$$

4 Recurrences

Algorithms analysis

E Zexal的二叉树 (签到)

题目

知识点：树，数论，dp，进阶（都可以做）
上学期我们学习了二叉树，也都知道3个结点的二叉树有5种。现给你二叉树的结点个数n，要你输出不同形态二叉树的种类数。

输入

第一个数为一个整数n($n \leq 30$)

输出

对于每组数据，输出一行，不同形态二叉树的种类数。

输入样例

3

输出样例

5

catalan数，卡特兰数，是一个常出现在各种计数问题中的数列，以比利时的数学家欧仁-查理-卡特兰命名

Dynamic Programming to solve MCM:

Four Steps

Step 1: The structure of an optimal parenthesization

$$\begin{array}{c} ((\underline{A_1 A_2 A_3}) (A_4 A_5)) ? \quad (A_1 A_2) (A_3 A_4 A_5) ? \quad \dots \\ \swarrow \qquad \searrow \\ (\underline{A_1} (\underline{A_2 A_3})) ? \quad ((\underline{A_1 A_2}) \underline{A_3}) ? \end{array}$$

$$(\underline{(\underline{A_i} (\underline{A_{i+1} \dots} (\dots) \dots A_k)} \underline{(A_{k+1} \dots A_{j-1} A_j)})})$$

Find the **optimal substructure**

$A_{i..j}$ (where $i \leq j$) : the product $A_i A_{i+1} \dots A_k A_{k+1} \dots A_j$

- $i < j$, **nontrivial**, any parenthesization of the product $A_i A_{i+1} \dots A_j$ must **split** the product between A_k and A_{k+1} for some integer k in the range $i \leq k < j$.
- First compute $A_{i..k}$, and $A_{k+1..j}$, then $A_{i..k} \cdot A_{k+1..j} = A_{i..j}$

The cost of this parenthesization $A_i A_{i+1} \dots A_j$

= the cost of computing the matrix $A_{i..k}$ + the cost of computing $A_{k+1..j}$
+ the cost of multiplying $A_{i..k} \cdot A_{k+1..j}$

Step 1: The structure of an optimal parenthesization

The optimal substructure

- Suppose that an optimal parenthesization of $A_i A_{i+1} \dots A_j$ splits the product between A_k and A_{k+1} .

$$(\underbrace{(A_i (A_{i+1} \dots) (\dots) \dots A_k)}_{\text{部分之积}}) \underbrace{(A_{k+1} \dots A_{j-1} A_j)}_{\text{部分之积}})$$

设矩阵连乘的最佳全括号将矩阵连乘分成 $A_{i..k}$ 和 $A_{k+1..j}$ 两部分之积

- The parenthesization of the "prefix" subchain $A_i A_{i+1} \dots A_k$ within this **optimal** parenthesization of $A_i A_{i+1} \dots A_j$ must be an **optimal** parenthesization of $A_i A_{i+1} \dots A_k$?

$A_{i..j}$ 的最佳全括号中的 $A_{i..k}$ 的全括号必定是 $A_{i..k}$ 的最佳全括号

$$(\underbrace{(A_i (A_{i+1} \dots) (\dots) \dots A_k)}_{\text{部分之积}}) \underbrace{(A_{k+1} \dots A_{j-1} A_j)}_{\text{部分之积}})$$

Proof



如果 X 最优，则 M 最优

Step 1: The structure of an optimal parenthesization

The optimal substructure

- The parenthesization of the "prefix" subchain $A_i A_{i+1} \dots A_k$ within this optimal parenthesization of $A_i A_{i+1} \dots A_j$ must be an optimal parenthesization of $A_i A_{i+1} \dots A_k$?

Proof Optimal parenthesization $A_{i..j} = (A_i \dots A_k) (A_{k+1} \dots A_j) = M \cdot N$, parenthesization $M = (A_i A_{i+1} \dots A_k)$ in $A_{i..j}$ above.

If there were a less costly way to parenthesize $A_i \dots A_k = P$, substituting M with P , that is $P \cdot N$ would produce another parenthesization of $A_{i..j}$ whose cost was lower than $M \cdot N$.

A contradiction.

- A similar observation holds for $A_{k+1} A_{k+2} \dots A_j$

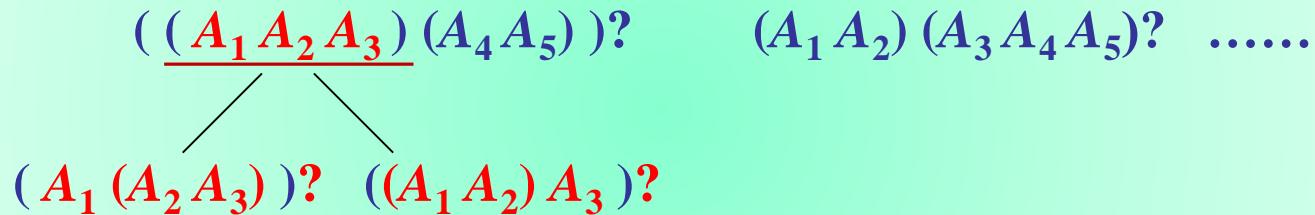
Step 1: The structure of an optimal parenthesization

$$(\underbrace{(A_i (A_{i+1} \dots) (\dots) \dots A_k)}_{M} (A_{k+1} \dots A_{j-1} A_j)) \quad X$$

- Construct an optimal solution to the problem X from optimal solutions to subproblems M based on optimal substructure.
from M to X
- Any solution to the matrix-chain multiplication requires us to split the product, and any optimal solution contains within it optimal solutions to subproblem instances.
 - Split the problem into two subproblems (optimally parenthesizing $A_i A_{i+1} \dots A_k$ and $A_{k+1} A_{k+2} \dots A_j$);
 - find optimal solutions to subproblem M ;
 - combine these optimal subproblem solutions (from M to X)

Step 1: The structure of an optimal parenthesization

$A_1 A_2 A_3 A_4 A_5$



($(A_i (A_{i+1} \dots) (\dots) \dots A_k)$) $(A_{k+1} \dots A_{j-1} A_j)$)

We must consider all possible places so that we are sure of having examined the optimal one.

需要考慮所有分割位置以確保最优解是其中之一

Step 2: A recursive solution

$$(\underbrace{(A_i(A_{i+1}\dots)(\dots)\dots A_k)}_{\text{子问题}}) \underbrace{(A_{k+1}\dots A_{j-1}A_j)}_{\text{剩余部分}})$$

- Define the cost of an optimal solution recursively in terms of the optimal solutions to subproblems.
根据子问题的最优解可以递归地定义原问题的最优解
- Subproblems $A_{i..j}$: determining the minimum cost of a parenthesization of $A_i A_{i+1} \dots A_j$ for $1 \leq i \leq j \leq n$.

Not $A_1 A_2 \dots A_j$, Why?

Step 2: A recursive solution

$$\left(\underbrace{(A_i (A_{i+1} \dots) (\dots) \dots A_k)}_{M} \right) \left(A_{k+1} \dots A_{j-1} A_j \right)$$

$$m[i, j] = |X| :$$

the minimum # of scalar multiplications to compute $A_{i..j}$;
the cost of a cheapest way to compute $A_{1..n}$ is $m[1, n]$.

- If $i = j$, one matrix $A_{i..i} = A_i$, no scalar multiplications.
Thus, $m[i, i] = 0$ for $i = 1, 2, \dots, n$.
- When $i < j$?

Step 2: A recursive solution

$$(\underbrace{(A_i(A_{i+1}\dots)(\dots)\dots A_k)}_{\text{Red line}})(A_{k+1}\dots A_{j-1}A_j)$$

$m[i,j]$:

When $i < j$, assuming that the optimal parenthesization splits $A_i A_{i+1} \dots A_j$ between A_k and A_{k+1} , where $i \leq k < j$.

Then,

$$m[i,j] = m[i,k] + m[k+1,j] + p_{i-1} p_k p_j$$



$m[i,j] =$ the minimum cost for computing $A_{i..k}$
+ the minimum cost for computing $A_{k+1..j}$
+ the cost of multiplying $A_{i..k}$ and $A_{k+1..j}$

A_i has dimensions $p_{i-1} \times p_i$, then $A_{i..k}$ has $p_{i-1} \times p_k$, $A_{k+1..j}$ has $p_k \times p_j$.

Step 2: A recursive solution

$$(\underbrace{(A_i(A_{i+1}\dots)(\dots)\dots A_k)}_{\text{Red line}})(A_{k+1}\dots \underbrace{A_{j-1}A_j}_{\text{Red line}})$$

$$m[i, j] = m[i, k] + m[k+1, j] + p_{i-1}p_k p_j$$

- This recursive equation assumes that we know the value of k , which we actually do not know.
- Only $j-i$ possible values for k , namely $k = i, i+1, \dots, j-1$.
- Checking them all to find the best k , we have

$$m[i, j] = \begin{cases} 0 & , \quad \text{if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k+1, j] + p_{i-1}p_k p_j\}, & \quad \text{if } i < j. \end{cases} \quad (15.12)$$

- The $m[i, j]$ give the costs of optimal solutions to subproblems.

Step 2: A recursive solution

$$(\underbrace{(A_i(A_{i+1}\dots)(\dots)\dots A_k)}_{\text{Red line}}) \underbrace{(A_{k+1}\dots A_{j-1}A_j)}_{\text{Red line}})$$

$$m[i, j] = \begin{cases} 0 & , \quad \text{if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k + 1, j] + p_{i-1}p_k p_j\}, & \quad \text{if } i < j. \end{cases} \quad (15.12)$$

Construct an optimal solution :

Define $s[i, j]$ to be a value of k at which we can split the product $A_i A_{i+1} \dots A_j$ to obtain an optimal parenthesization. That is, $s[i, j]$ equals a value k such that $m[i, j] = m[i, k] + m[k + 1, j] + p_{i-1}p_k p_j$.

Step 3: Computing the optimal costs

$$m[i, j] = \begin{cases} 0 & , \quad \text{if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k+1, j] + p_{i-1}p_kp_j\}, & \text{if } i < j. \end{cases} \quad (15.12)$$

recursive algorithm based on recurrence (15.12)?

$m[1, n]$ for multiplying $A_1A_2\dots A_n$.

RE-MCM(p, i, j)

```
1 if  $i = j$ 
2   return 0
3  $m[i, j] \leftarrow \infty$ 
4 for  $k \leftarrow i$  to  $j-1$ 
5    $q \leftarrow \text{RE-MCM}(p, i, k) + \text{RE-MCM}(p, k+1, j) + p_{i-1}p_kp_j$ 
6   if  $q < m[i, j]$ 
7      $m[i, j] \leftarrow q$ 
8 return  $m[i, j]$ 
```

Running time?

Step 3: Computing the optimal costs

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k+1, j] + p_{i-1} p_k p_j\}, & \text{if } i < j. \end{cases} \quad (15.12)$$

```

RE-MCM( $p, i, j$ )
1 if  $i = j$ 
2   return 0
3    $m[i, j] \leftarrow \infty$ 
4   for  $k \leftarrow i$  to  $j-1$ 
5      $q \leftarrow \text{RE-MCM}(p, i, k)$ 
       +  $\text{RE-MCM}(p, k+1, j)$ 
       +  $p_{i-1} p_k p_j$ 
6     if  $q < m[i, j]$ 
7        $m[i, j] \leftarrow q$ 
8   return  $m[i, j]$ 

```

$T(n)$
1
1
1
1
$T(k)$
$T(n-k)$
1
1
1
1

$$\begin{aligned}
T(n) &\geq 1 + \sum_{k=1}^{n-1} (T(k) + T(n-k) + 1) \\
&= 2 \sum_{i=1}^{n-1} T(i) + n \geq 3^n
\end{aligned}$$

Proof

let $T(i) \geq 3^i$,

then $T(n) \geq 2 \sum_{i=1}^{n-1} T(i) + n$

$$\begin{aligned}
&\geq 2 \times (3^1 + 3^2 + \dots + 3^{n-1}) + n \\
&\geq 2 \times 3 \frac{3^{n-1} - 1}{3 - 1} + n \\
&= 3^n - 3 + n \geq 3^n
\end{aligned}$$

This algorithm takes **exponential** time, which is no better than the brute-force method of checking each way of parenthesizing the product. Why?

$$P(n) = \begin{cases} 1 & , \text{ if } n=1, \\ \sum_{k=1}^{n-1} P(k)P(n-k), & \text{if } n \geq 2. \end{cases} \quad (15.11)$$

$\Omega(2^n)$

Step 3: Computing the optimal costs

$$\frac{(\underbrace{(A_i(A_{i+1}\dots)(\dots)\dots A_k)}_{}, (A_{k+1}\dots A_{j-1}A_j))}{m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k + 1, j] + p_{i-1}p_kp_j\}, & \text{if } i < j. \end{cases}} \quad (15.12)$$

Recursion, Extremely slow!

of subproblems: one problem for each choice of i and j satisfying $1 \leq i \leq j \leq n$?
(所有子问题个数为?)

$$C_n^2 + n = \Theta(n^2)$$

$$1 \leq i = j \leq n, C_n^1 = n$$

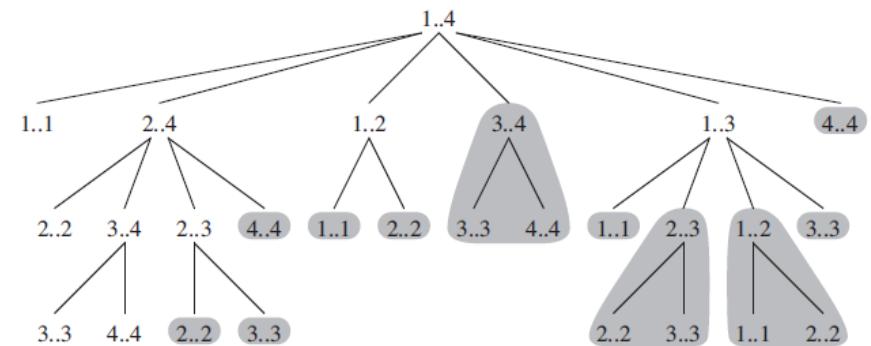
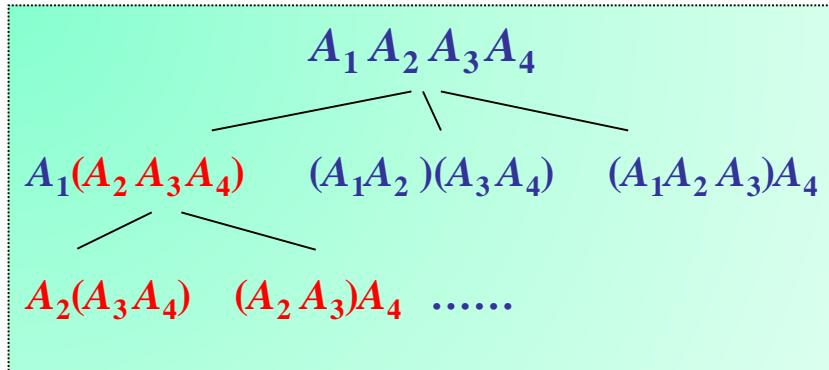
$$1 \leq i < j \leq n, C_n^2 = n(n-1)/2$$

Step 3: Computing the optimal costs

$$\underline{\underline{(\ A_i(A_{i+1}\dots)(\dots)\dots A_k) \ (A_{k+1}\dots \ A_{j-1}A_j) \)}}$$

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k + 1, j] + p_{i-1}p_kp_j\}, & \text{if } i < j. \end{cases} \quad (15.12)$$

- A recursive algorithm may encounter each subproblem **many times** in different branches of its recursion tree.
- **Overlapping subproblems:** the second hallmark of the applicability of dynamic programming.

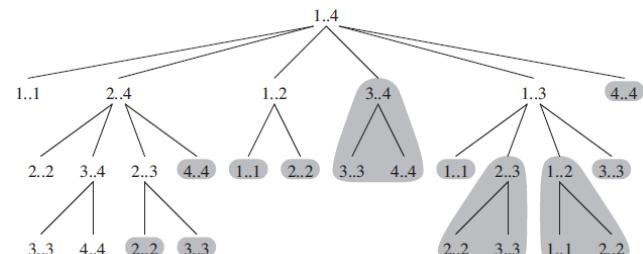


Step 3: Computing the optimal costs

$$\underline{\quad \quad \quad (A_i (A_{i+1} \dots) (\dots) \dots A_k) (A_{k+1} \dots A_{j-1} A_j) \quad \quad \quad }$$

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{ m[i, k] + m[k + 1, j] + p_{i-1} p_k p_j \}, & \text{if } i < j. \end{cases} \quad (15.12)$$

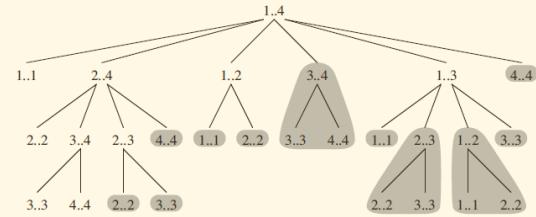
- **# of subproblems: one problem for each choice of i and j satisfying $1 \leq i \leq j \leq n$, or $\binom{n}{2} + n = \Theta(n^2)$ in all.** (子问题个数为 $\Theta(n^2)$)
- Instead of recursive method, computing the optimal cost by using a tabular, bottom-up approach.
不用递归方法，而采用列表方式、自底向上的方法计算最优解



Step 3: Computing the optimal costs

$$((A_i (A_{i+1} \dots) (\dots) \dots A_k) (A_{k+1} \dots A_{j-1} A_j))$$

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{ m[i, k] + m[k+1, j] + p_{i-1} p_k p_j \}, & \text{if } i < j. \end{cases} \quad (15.12)$$



A_i : dimensions $p_{i-1} \times p_i$

Input: $p = \langle p_0, p_1, \dots, p_n \rangle$.

Procedure: Table $m[1..n, 1..n]$ storing the $m[i, j]$ costs;

Auxiliary table $s[1..n, 1..n]$ recording which index of k achieved the optimal cost in computing $m[i, j]$.

计算 $m[i, j]$ 时, 用辅助表项(table entry) $s[i, j]$ 来记录最佳位置 k 的值

MCM-DP(p)

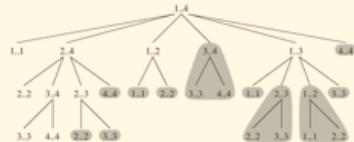
```

1   $n \leftarrow \text{length}[p] - 1$ 
2  for  $i \leftarrow 1$  to  $n$ 
3     $m[i, i] \leftarrow 0$ 
4  for  $l \leftarrow 2$  to  $n$           //  $l$  is the chain length.
5    for  $i \leftarrow 1$  to  $n - l + 1$ 
6       $j \leftarrow i + l - 1$ 
7       $m[i, j] \leftarrow \infty$ 
8      for  $k \leftarrow i$  to  $j - 1$ 
9         $q \leftarrow m[i, k] + m[k+1, j] + p_{i-1} p_k p_j$ 
10       if  $q < m[i, j]$ 
11          $m[i, j] \leftarrow q$ 
12          $s[i, j] \leftarrow k$ 
13  return  $m$  and  $s$ 
```

Step 3: Computing the optimal costs

($(A_i(A_{i+1} \dots) \dots A_k)(A_{k+1} \dots A_{j-1}A_j)$)

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k+1, j] + p_{i-1}p_kp_j\}, & \text{if } i < j. \end{cases} \quad (15.12)$$



MCM-DP(p)

```

1  $n \leftarrow \text{length}[p] - 1$ 
2 for  $i \leftarrow 1$  to  $n$ 
3    $m[i, i] \leftarrow 0$ 
4 for  $l \leftarrow 2$  to  $n$            //  $l$  is the chain length.
5   for  $i \leftarrow 1$  to  $n - l + 1$ 
6      $j \leftarrow i + l - 1$ 
7      $m[i, j] \leftarrow \infty$ 
8     for  $k \leftarrow i$  to  $j - 1$ 
9        $q \leftarrow m[i, k] + m[k+1, j] + p_{i-1}p_kp_j$ 
10      if  $q < m[i, j]$ 
11         $m[i, j] \leftarrow q$ 
12         $s[i, j] \leftarrow k$ 
13 return  $m$  and  $s$ 
```

A_1	30×35
A_2	35×15
A_3	15×5
A_4	5×10
A_5	10×20
A_6	20×25

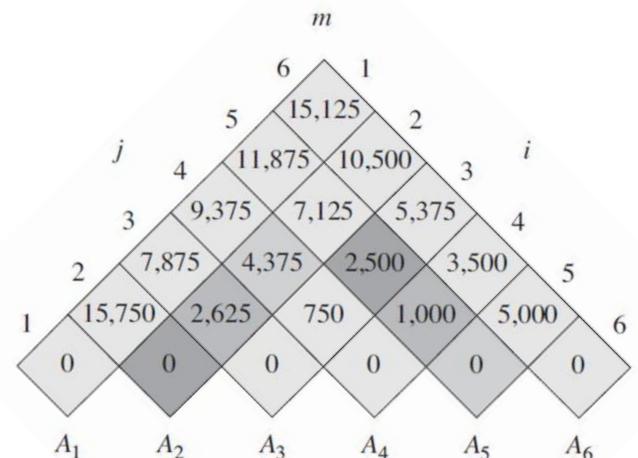
i	1	2	3	4	5	6
0	0	15,750	7,875	9,375	11,875	15,125
1		0	2,625	4,375	7,125	10,500
2			0	750	2,500	5,375
3				0	1,000	3,500
4					0	5,000
5						0

i	1	2	3	4	5	6
1	1	1	3	3	3	1
2		2	3	3	3	2
3			3	3	3	3
4				4	5	4
5					5	5

Step 3: Computing the optimal costs

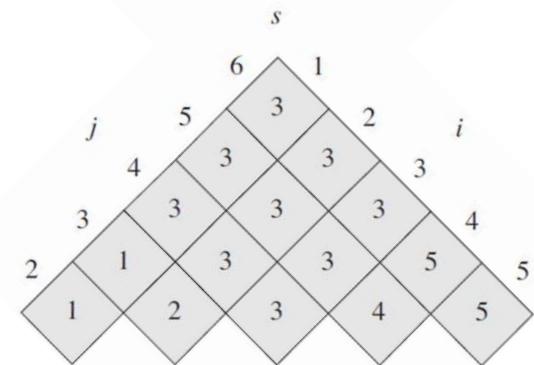
	1	2	3	4	5	6	m
1	0	15,750	7,875	9,375	11,875	15,125	
2		0	2,625	4,375	7,125	10,500	
3			0	750	2,500	5,375	
4				0	1,000	3,500	
5					0	5,000	
6						0	

rotate 45°



	1	2	3	4	5	6	s
1	1	1	3	3	3	3	
2		2	3	3	3	3	
3			3	3	3	3	
4				3	3	3	
5					3	3	
6						3	

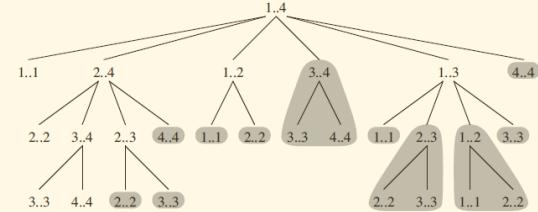
rotate 45°



Step 3: Computing the optimal costs

$$((A_i (A_{i+1} \dots) (\dots) \dots A_k) (A_{k+1} \dots A_{j-1} A_j))$$

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k + 1, j] + p_{i-1} p_k p_j\}, & \text{if } i < j. \end{cases} \quad (15.12)$$

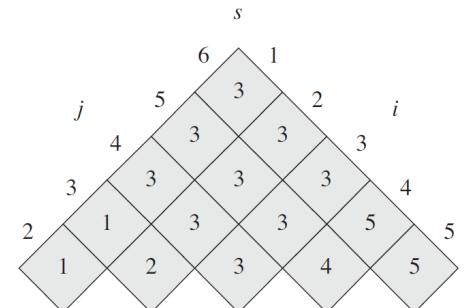
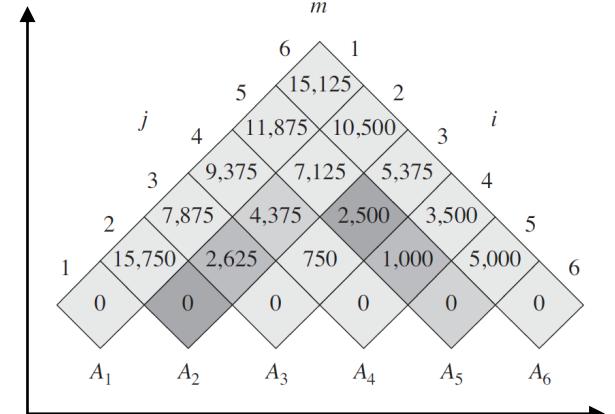


MCM-DP(p)

```

1  $n \leftarrow \text{length}[p] - 1$ 
2 for  $i \leftarrow 1$  to  $n$ 
3    $m[i, i] \leftarrow 0$ 
4 for  $l \leftarrow 2$  to  $n$  //  $l$  is the chain length.
5   for  $i \leftarrow 1$  to  $n - l + 1$ 
6      $j \leftarrow i + l - 1$ 
7      $m[i, j] \leftarrow \infty$ 
8     for  $k \leftarrow i$  to  $j - 1$ 
9        $q \leftarrow m[i, k] + m[k + 1, j] + p_{i-1} p_k p_j$ 
10      if  $q < m[i, j]$ 
11         $m[i, j] \leftarrow q$ 
12         $s[i, j] \leftarrow k$ 
13 return  $m$  and  $s$ 
```

A_1	30×35
A_2	35×15
A_3	15×5
A_4	5×10
A_5	10×20
A_6	20×25



Step 3: Computing the optimal costs

```
MCM-DP( $p$ )
1  $n \leftarrow \text{length}[p] - 1$ 
2 for  $i \leftarrow 1$  to  $n$ 
3    $m[i, i] \leftarrow 0$ 
4 for  $l \leftarrow 2$  to  $n$       //  $l$  is the chain length.
5   for  $i \leftarrow 1$  to  $n - l + 1$ 
6      $j \leftarrow i + l - 1$ 
7      $m[i, j] \leftarrow \infty$ 
8     for  $k \leftarrow i$  to  $j - 1$ 
9        $q \leftarrow m[i, k] + m[k+1, j] + p_{i-1}p_kp_j$ 
10      if  $q < m[i, j]$ 
11         $m[i, j] \leftarrow q$ 
12         $s[i, j] \leftarrow k$ 
13 return  $m$  and  $s$ 
```

The running time?
Space requirement?

Time : $T(n) = O(n^3)$
Space: $S(n) = \Theta(n^2)$

Step 3: Computing the optimal costs

MCM-DP(p)

```
1  $n \leftarrow \text{length}[p] - 1$ 
2 for  $i \leftarrow 1$  to  $n$ 
3    $m[i, i] \leftarrow 0$ 
4 for  $l \leftarrow 2$  to  $n$            //  $l : n-1$  times
5   for  $i \leftarrow 1$  to  $n - l + 1$     //  $i : n-l+1$  times
6      $j \leftarrow i + l - 1$ 
7      $m[i, j] \leftarrow \infty$ 
8     for  $k \leftarrow i$  to  $j - 1$     //  $k : j-i=l-1$  times
9        $q \leftarrow m[i, k] + m[k+1, j] + p_{i-1}p_kp_j$ 
10      if  $q < m[i, j]$ 
11         $m[i, j] \leftarrow q$ 
12         $s[i, j] \leftarrow k$ 
13 return  $m$  and  $s$ 
```

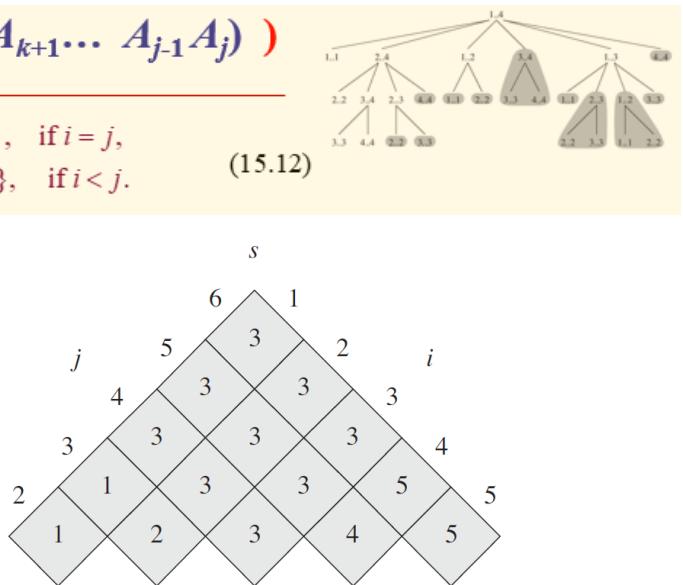
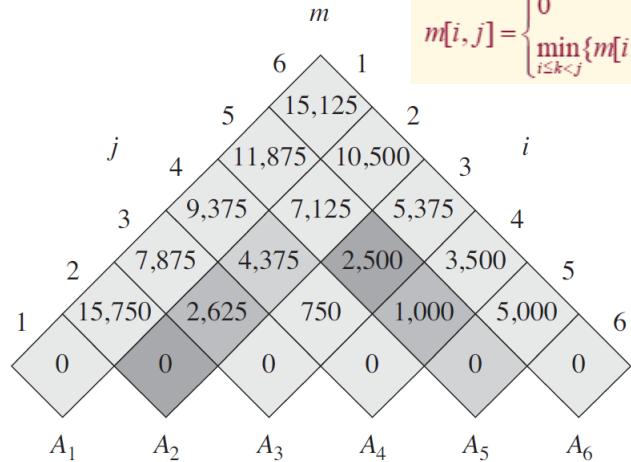
Exercise:

$$T(n) = \sum_{l=2}^n (n-l+1)(l-1)$$

The running time?

Step 4: Constructing an optimal solution

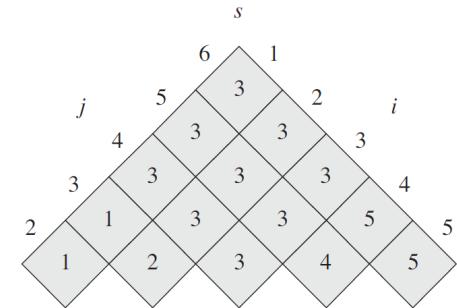
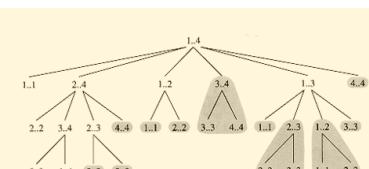
$$m[i,j] = \begin{cases} 0 & , \text{ if } i=j, \\ \min_{i \leq k < j} \{ m[i,k] + m[k+1,j] + p_{i-1} p_k p_j \}, & \text{if } i < j. \end{cases} \quad (15.12)$$



- MCM-DP determines the optimal number $m[i, j]$, but does not directly show how to multiply the matrices.
算法MCM-DP 给出了如何求解最佳乘法次数 $m[i, j]$, 但对于按什么顺序来相乘各矩阵, 没有给出具体方法
 - Constructing an optimal solution from table $s[1.. n-1, 2.. n]$.

Step 4: Constructing an optimal solution

$$\begin{array}{c}
 (\underline{(A_i(A_{i+1}\dots)(\dots)\dots A_k)}(\underline{A_{k+1}\dots A_{j-1}A_j})) \\
 \\[1em]
 m[i,j] = \begin{cases} 0 & \text{if } i = j, \\ \min_{i \leq k < j} \{m[i,k] + m[k+1,j] + p_{i-1}p_kp_j\}, & \text{if } i < j. \end{cases} \quad (15.12)
 \end{array}$$

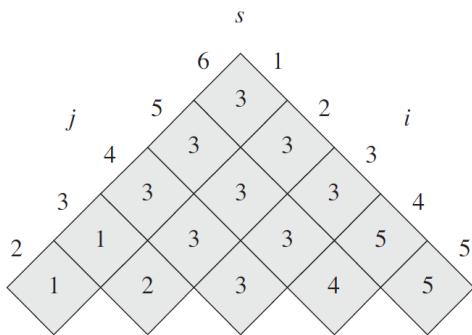


- Each entry $s[i, j]$ records the value of k such that the optimal parenthesization of $A_i A_{i+1} \cdots A_j$ splits the product between A_k and A_{k+1} . Thus, the final matrix multiplication in computing $A_{1..n}$ optimally is $A_{1..s[1,n]} A_{s[1,n]+1..n}$.
 $s[i, j]$ 记录值 k ，表示在矩阵连乘 $A_i A_{i+1} \cdots A_j$ 的最佳全括号中，分割点位于 A_k 和 A_{k+1} 之间。因此，矩阵连乘 $A_{1..n}$ 的最优分割方式为 $(A_1 A_2 \dots A_{s[1,n]})(A_{s[1,n]+1} \dots A_n)$.
 - The matrix multiplications can be computed recursively,
$$s[1, s[1, n]] \rightarrow \text{splits } A_{1..s[1, n]}$$

$$s[s[1, n] + 1, n] \rightarrow \text{splits } A_{s[1, n]+1..n}$$
- PRINT-OPTIMAL-PARENS(s, i, j)

Step 4: Constructing an optimal solution

PRINT-OPTIMAL-PARENS(s, i, j) printing an optimal parenthesization of $\langle A_i, A_{i+1}, \dots, A_j \rangle$ recursively, given the s table. The initial call $i=1, j=n$.



A_1 30×35
 A_2 35×15
 A_3 15×5
 A_4 5×10
 A_5 10×20
 A_6 20×25

PRINT-OPTIMAL-PARENS(s, i, j)

```
1 if  $i == j$ 
2   print " $A$ "i
3 else
4   print "("
5   PRINT-OPTIMAL-PARENS( $s, i, s[i, j]$ )
6   PRINT-OPTIMAL-PARENS( $s, s[i, j]+1, j$ )
7   print ")"
```

↓ How to work?

$((A_1(A_2A_3)) ((A_4A_5)A_6))$

Step 4: Constructing an optimal solution

PRINT-OPTIMAL-PARENS(s, i, j)

```

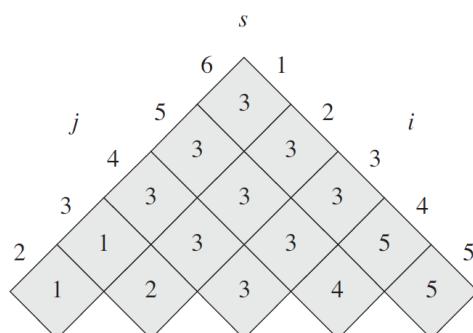
1 if  $i == j$ 
2   print " $A$ " $_i$ 
3 else
4   print "("
5   PRINT-OPTIMAL-PARENS( $s, i, s[i, j]$ )
6   PRINT-OPTIMAL-PARENS( $s, s[i, j]+1, j$ )
7   print ")"

```

$A_1 A_2 A_3 A_4 A_5 A_6$: $((A_1 A_2 A_3) (A_4 A_5) A_6)?$

$\begin{array}{c} / \quad \backslash \\ A_1 (A_2 A_3)? \quad (A_1 A_2) A_3? \end{array}$

A_1	30×35
A_2	35×15
A_3	15×5
A_4	5×10
A_5	10×20
A_6	20×25



$s(1,6)$

$(s(1,3) s(4,6))$

$(s(1,1) s(2,3))$

$(s(2,2) s(3,3))$

$((A_1(A_2A_3)) ((A_4A_5)A_6))$

?

Exercise-1 (in class)

$A_1 A_2 A_3 A_4 A_5$: $(A_1 A_2 A_3) (A_4 A_5)?$ $(A_1 A_2) (A_3 A_4 A_5)?$

$A_1 (A_2 A_3)?$ $(A_1 A_2) A_3?$

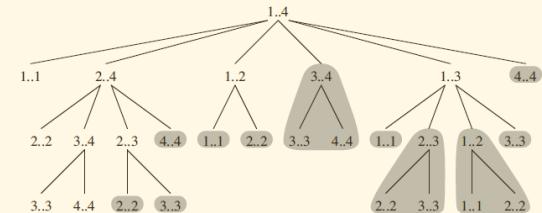
$$\left(\underline{(A_i (A_{i+1} \dots) (\dots) \dots A_k)} \right) \underline{(A_{k+1} \dots A_{j-1} A_j)})$$

- Brute force: exhaustively checking all possible parenthesizations.
- $P(n)$: the # of alternative parenthesizations of n matrices.
令 $P(n)$ 表示 n 个矩阵连乘时所有可能的全括号方式的个数
- What is the solution of $P(n)$?

Exercise-2 (in class)

$$((A_i (A_{i+1} \dots) (\dots) \dots A_k) (A_{k+1} \dots A_{j-1} A_j))$$

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k + 1, j] + p_{i-1} p_k p_j\}, & \text{if } i < j. \end{cases} \quad (15.12)$$



RE-MCM(p, i, j)

```

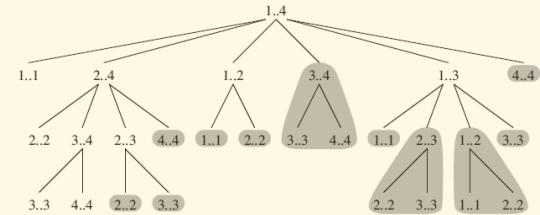
1 if  $i = j$ 
2   return 0
3  $m[i, j] \leftarrow \infty$ 
4 for  $k \leftarrow i$  to  $j-1$ 
5    $q \leftarrow \text{RE-MCM}(p, i, k) + \text{RE-MCM}(p, k+1, j) + p_{i-1} p_k p_j$ 
6   if  $q < m[i, j]$ 
7      $m[i, j] \leftarrow q$ 
8 return  $m[i, j]$ 
```

Running time ?

Exercise-3

$$((A_i (A_{i+1} \dots) (\dots) \dots A_k) (A_{k+1} \dots A_{j-1} A_j))$$

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{ m[i, k] + m[k + 1, j] + p_{i-1} p_k p_j \}, & \text{if } i < j. \end{cases} \quad (15.12)$$

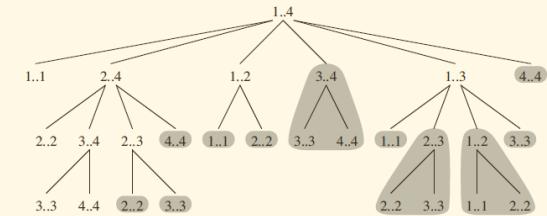


of subproblems: one problem for each choice of i and j satisfying $1 \leq i \leq j \leq n$? (所有子问题个数为?)

Exercise-4

$$((A_i (A_{i+1} \dots) (\dots) \dots A_k) (A_{k+1} \dots A_{j-1} A_j))$$

$$m[i, j] = \begin{cases} 0 & , \text{ if } i = j, \\ \min_{i \leq k < j} \{ m[i, k] + m[k + 1, j] + p_{i-1} p_k p_j \}, & \text{if } i < j. \end{cases} \quad (15.12)$$



Dynamic Programming:
top-down with
memoization?

15 Dynamic Programming

- ✓ Scheduling two automobile assembly lines
- ✓ Steel rod cutting (15.1)
- ✓ Matrix-chain multiplication (15.2)
- ✓ Characteristics(Elements) of dynamic programming (15.3)
- ✓ Longest common subsequence (15.4)
- ✓ Optimal binary search trees (15.5)
最优二叉搜索树

15.5 Optimal binary search trees

输入法的词库选择



15.5 Optimal binary search trees

Design a program to translate text from English to Chinese (翻译软件)

The screenshot shows a web browser window for Baidu Translate (<https://fanyi.baidu.com/>). The page displays an English text input and its corresponding French translation.

English Input:

Suppose that we are designing a program to translate text from English to French. For each occurrence of each English word in the text, we need to look up its French equivalent. We could perform these lookup operations by building a

French Translation:

假设我们正在设计一个程序来把文本从英语翻译成法语。对于每一个出现在文本中的每个英语单词，我们需要查找它的法语等价物。我们可以通过构建一个二进制搜索树来执行这些查找操作，其中n个英语单词作为关键字，它们的法语等价物作为卫星数据。

UI Elements:

- Top navigation bar: 百度翻译 (Baidu Translate), Baidu logo, and user info (136*****73).
- Input fields: 检测到英语 (Detected English) and 中文 (Chinese).
- Buttons: 翻译 (Translate) and 人工翻译 (Human Translation).
- Bottom right: QR code for Baidu Translate APP, text: 百度翻译APP 各大应用商店 精品推荐.

Bottom Left:

- Sort button: 排序.
- Vocabulary section: 重点词汇 (Key Vocabulary).
 - Suppose that 假如
 - designing 狡诈的, 狡猾的, 诡计多端的; 设计; 设计, ...
 - translate 翻译; 转化; 解释; 被翻译

15.5 Optimal binary search trees

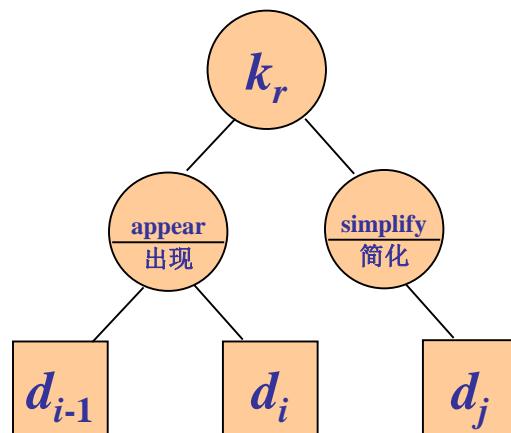
Design a program to translate text from English to Chinese

检测到英语 ▾ ⇛ 中文 ▾ 翻译 人工翻译 ⌂ ⚙

Suppose that we are designing a program to translate text from English to French. For each occurrence of each English word in the text, we need to look up its French equivalent. We could perform these lookup operations by building a

假设我们正在设计一个程序来把文本从英语翻译成法语。对于每一个出现在文本中的每个英语单词，我们需要查找它的法语等价物。我们可以通过构建一个二进制搜索树来执行这些查找操作，其中n个英语单词作为关键字，它们的法语等价物作为卫星数据。

ⓘ ⭐ ⓘ ⚙ 报错 拼音 双语对照



生词表	
字段1	字段2
aggregate	综合, 总体
amortized	分摊, 平摊
arbitrary	任意的, 武断的
auxiliary	辅助的
binomial	二项的, 二项式的
bog	沼泽, 陷于泥沼
...	...
suppose	假设
...	...

15.5 Optimal binary search trees

- Design a program to translate text from English to Chinese
- an $O(n)$ search time per occurrence by using any linear table operation



生词表	
字段1	字段2
aggregate	综合, 总体
amortized	分摊, 平摊
arbitrary	任意的, 武断的
auxiliary	辅助的
binomial	二项的, 二项式的
bog	沼泽, 陷于泥沼
...	...
suppose	假设
...	...

15.5 Optimal binary search trees

Sogou Input Method
个性化设置向导

选择您所需要的细胞词库：

<input type="checkbox"/> 动物词汇	<input checked="" type="checkbox"/> 计算机名词
<input type="checkbox"/> 足球词库	<input type="checkbox"/> 篮球词库
<input type="checkbox"/> 中医中药	<input type="checkbox"/> 劲舞团
<input type="checkbox"/> 魔兽世界	<input type="checkbox"/> 跑跑卡丁车
<input type="checkbox"/> 地下城与勇士DNF	<input type="checkbox"/> 奇迹世界

Dict.cn 福词

在线中英文短文翻译

请输入要翻译的短文。(系统会自动进行英汉互译)

Given an algorithm, you can improve on the time or space it uses. Some changes can simplify the code and improve constant factors but yield no asymptotic improvement in performance.

开始翻译

译文如下

给算法，您能改善在时间或空间它用途。一些变动无法简化代码和改进恒定的因素只是产生在表现的渐进改善。

Baidu 翻译

百度wifi翻译机 热 人工翻译 下载翻译插件

检测到英语 中文 翻译 人工翻译

Suppose that we are designing a program to translate text from English to French. For each occurrence of each English word in the text, we need to look up its French equivalent. We could perform these lookup operations by building a

假设我们正在设计一个程序来对于每一个出现在文本中的每它的法语等价物。我们可以通执行这些查找操作，其中 n 个英的法语等价物作为卫星数据。

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http://www.lingoes.cn/zh/dictionary/dict_cata.php?cata=4

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CFA 特许金融分析师词汇

共6页: 1 2 3 4 5 6

算法是软件的灵魂

算法是企业生产力

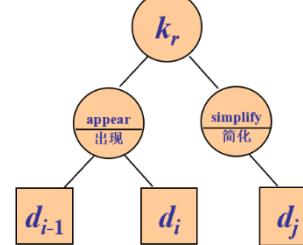
15.5 Optimal binary search trees

- **lookup operations:**
build a binary search tree (BST) with
 - ◆ ***n* English words as keys**
 - ◆ **Chinese equivalents as satellite data 从属数据**

检测到英语 ⇄ 中文 翻译 人工翻译 ⌂ ⚙

Suppose that we are designing a program to translate text from English to French. For each occurrence of each English word in the text, we need to look up its French equivalent. We could perform these lookup operations by building a

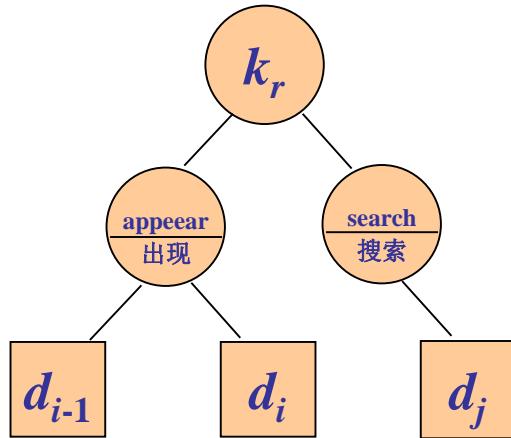
假设我们正在设计一个程序来把文本从英语翻译成法语。对于每一个出现在文本中的每个英语单词，我们需要查找它的法语等价物。我们可以通过构建一个二进制搜索树来执行这些查找操作，其中*n*个英语单词作为关键字，它们的法语等价物作为卫星数据。



生词表	
字段1	字段2
aggregate	综合, 总体
amortized	分摊, 平摊
arbitrary	任意的, 武断的
auxiliary	辅助的
binomial	二项的, 二项式的
bog	沼泽, 陷于泥沼
...	...
suppose	假设
...	...

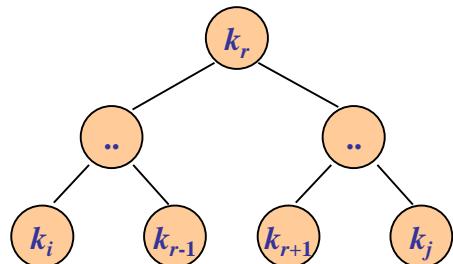
- Because we will search the tree for each individual word in the text, we want the total time spent searching to be as low as possible. 对于课文中出现的每个单词，都需要搜索该二叉树，如何使得总的搜索次数最少？
- an $O(\lg n)$ search time per occurrence by using any balanced BST. 对于任何一个单词的搜索，使用二分搜索法的时间为 $O(\lg n)$.

15.5 Optimal binary search trees



生词表	
字段1	字段2
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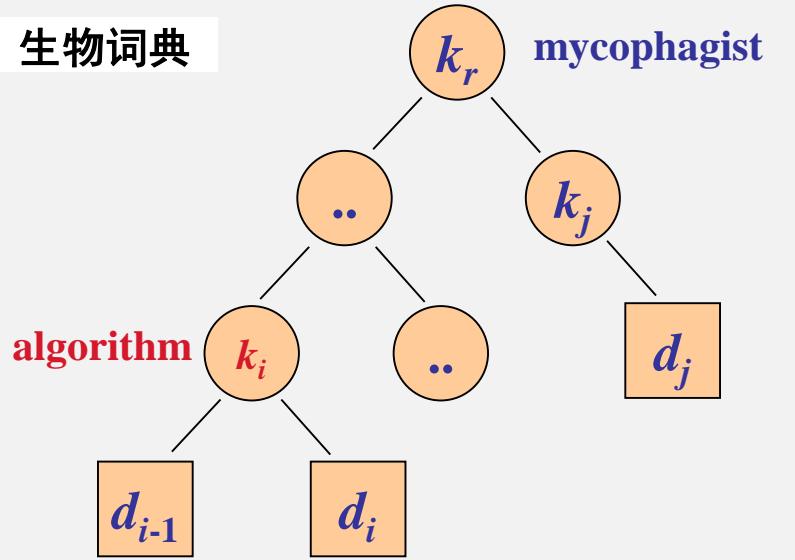
A balanced BST...



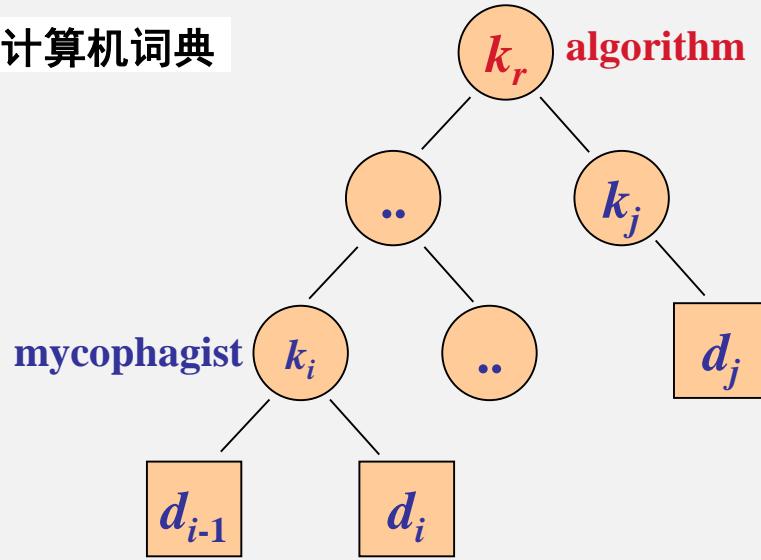
However, Words appear with different frequencies...?

15.5 Optimal binary search trees

生物词典



计算机词典



- Words appear with different frequencies
- It may be: “algorithm” (frequently used) appears far from the root; “mycophagist” (rarely used, 食菌者) appears near the root
- Such an organization would slow down the translation, since # of nodes visited when searching for a key in a BST is $1 + \text{depth}$
- We want words that occur frequently in the text to be placed nearer the root

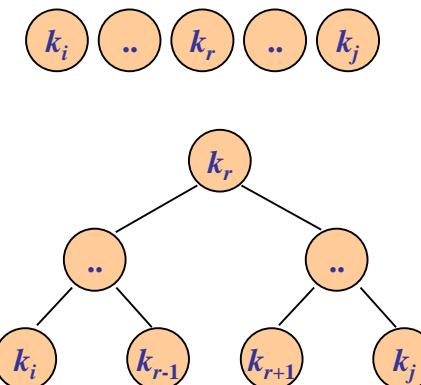
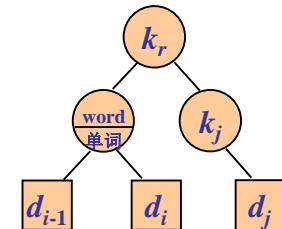
15.5 Optimal binary search trees

- Need the total time spent searching to be as low as possible.
- We want words that occur frequently in the text to be placed nearer the root.
- Moreover, there may be words in the text for which there is no Chinese translation, and such words might not appear in the BST at all.

文中有些英语单词没有对应的汉语译文，即这些英语单词不出现在二叉搜索树“词典”中

- How do we organize a BST so as to minimize the number of nodes visited in all searches, given that we know how often each word occurs?

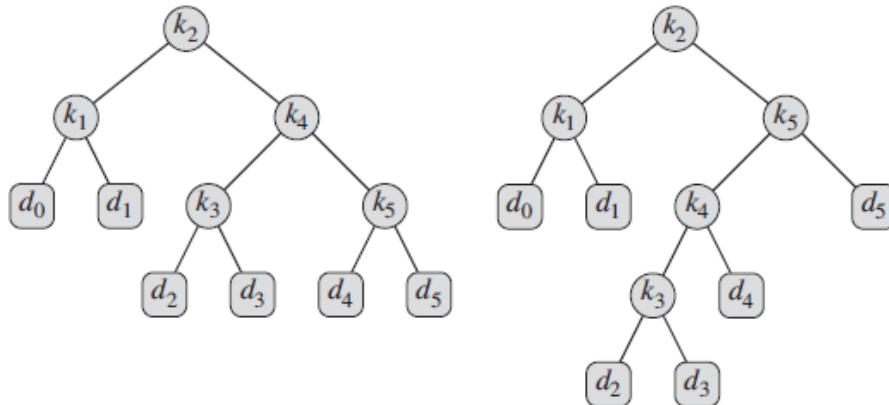
设已知每个单词出现的概率，如何组织一颗二叉搜索树，使得在所有搜索中，被访问的节点的总数最少？



15.5 Optimal binary search trees

BST: Given a sequence $K = \langle k_1, k_2, \dots, k_n \rangle$ of n distinct keys in sorted order ($k_1 < k_2 < \dots < k_n$), how to build a BST?

- For key k_i , search probability p_i (it can also be the number I of occurrence of k_i in the text, whose number of total words is M , then $p_i = I / M$.)
- Some values not in K , $n+1$ "dummy keys" d_0, d_1, \dots, d_n
- d_0 represents all values $< k_1$; d_n represents all values $> k_n$
- for $1 \leq i \leq n-1$, $d_i : k_i < d_i < k_{i+1}$, search probability q_i
- Fig, each key k_i , an internal node; d_i , a leaf



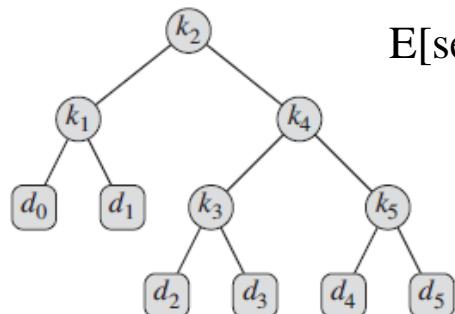
i	0	1	2	3	4	5
p_i		0.15	0.10	0.05	0.10	0.20
q_i	0.05	0.10	0.05	0.05	0.05	0.10

15.5 Optimal binary search trees

- Every search is either successful or unsuccessful, we have

$$\sum_{i=1}^n p_i + \sum_{i=0}^n q_i = 1 \quad (15.15)$$

- We have probabilities of searches for each (dummy) key, we can determine the expected cost of a search in a given BST T .
- Assume that the actual cost of a search is the number of nodes examined. Then the expected cost of a search in T is



$$\begin{aligned} E[\text{search cost in } T] &= \sum_{i=1}^n (\text{depth}_T(k_i) + 1) \cdot p_i + \sum_{i=0}^n (\text{depth}_T(d_i) + 1) \cdot q_i \\ &= 1 + \sum_{i=1}^n \text{depth}_T(k_i) \cdot p_i + \sum_{i=0}^n \text{depth}_T(d_i) \cdot q_i , \end{aligned} \quad (15.16)$$

where depth_T denotes a node's depth in the tree T . (树根高度为0)

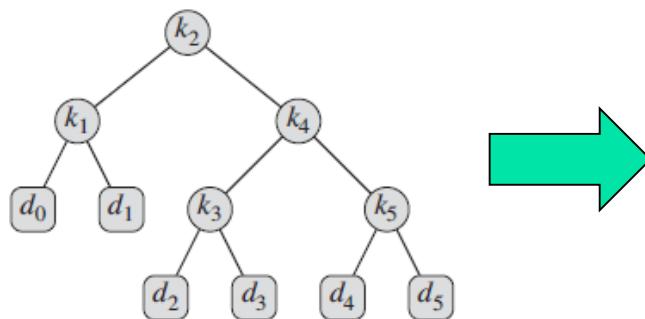
15.5 Optimal binary search trees

$E[\text{search cost in } T]$

$$= \sum_{i=1}^n (\text{depth}_T(k_i) + 1) \cdot p_i + \sum_{i=0}^n (\text{depth}_T(d_i) + 1) \cdot q_i$$

$$= 1 + \sum_{i=1}^n \text{depth}_T(k_i) \cdot p_i + \sum_{i=0}^n \text{depth}_T(d_i) \cdot q_i$$

In Figure 15.7(a), we can calculate the expected search cost node by node:



node	depth	probability	contribution
k_1	1	0.15	0.30
k_2	0	0.10	0.10
k_3	2	0.05	0.15
k_4	1	0.10	0.20
k_5	2	0.20	0.60
d_0	2	0.05	0.15
d_1	2	0.10	0.30
d_2	3	0.05	0.20
d_3	3	0.05	0.20
d_4	3	0.05	0.20
d_5	3	0.10	0.40
Total			2.80

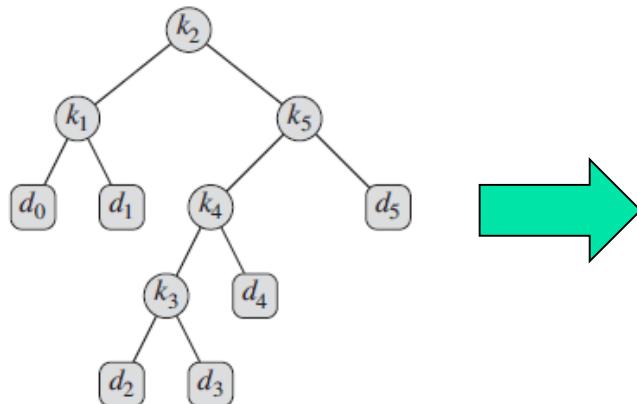
15.5 Optimal binary search trees

$E[\text{search cost in } T]$

$$= \sum_{i=1}^n (\text{depth}_T(k_i) + 1) \cdot p_i + \sum_{i=0}^n (\text{depth}_T(d_i) + 1) \cdot q_i$$

$$= 1 + \sum_{i=1}^n \text{depth}_T(k_i) \cdot p_i + \sum_{i=0}^n \text{depth}_T(d_i) \cdot q_i$$

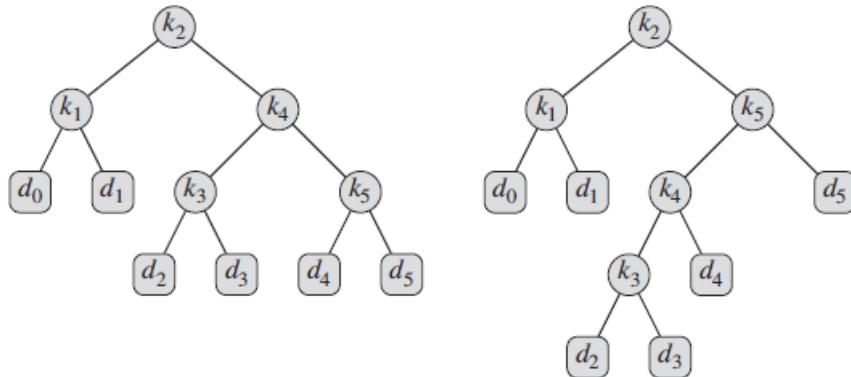
In Figure 15.7(b)



node	depth	probability	contribution
k_1	1	0.15	0.30
k_2	0	0.10	0.10
k_3	3	0.05	0.20
k_4	2	0.10	0.30
k_5	1	0.20	0.40
d_0	2	0.05	0.15
d_1	2	0.10	0.30
d_2	4	0.05	0.25
d_3	4	0.05	0.25
d_4	3	0.05	0.20
d_5	2	0.10	0.30
Total			2.75

15.5 Optimal binary search trees

- **Optimal BST** : for a given set of probabilities, our goal is to construct a BST whose expected search cost is the **smallest**.



<i>i</i>	0	1	2	3	4	5
p_i		0.15	0.10	0.05	0.10	0.20
q_i	0.05	0.10	0.05	0.05	0.05	0.10

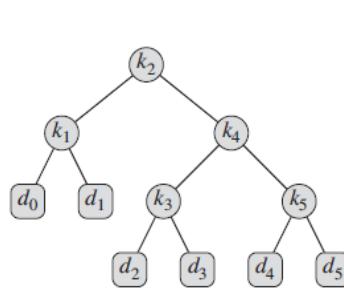
- How to build an OBST?

Intuitively,

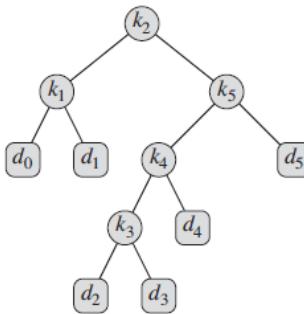
- ♦ the overall height is smallest
 - ♦ the key with the greatest probability at the root

15.5 Optimal binary search trees

- **Optimal BST** : for a given set of probabilities, our goal is to construct a BST whose expected search cost is the **smallest**.



(a) cost: 2.80



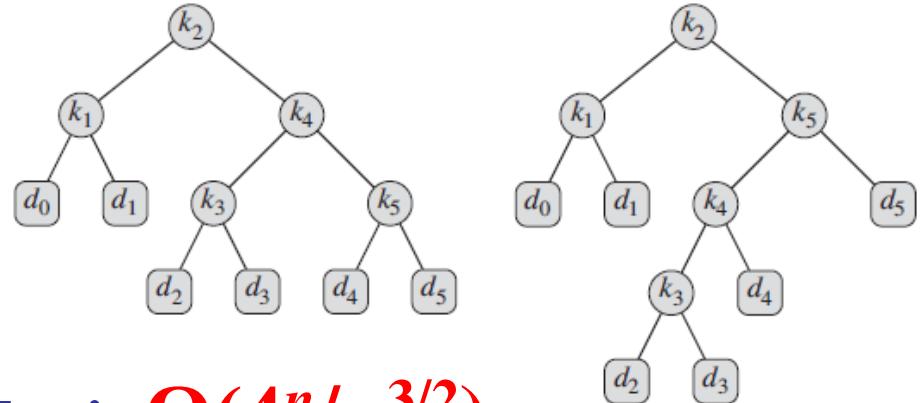
(b) cost: 2.75

i	0	1	2	3	4	5
p_i	0.15	0.10	0.05	0.10	0.20	
q_i	0.05	0.10	0.05	0.05	0.05	0.10

- Figure 15.7(b) shows an **Optimal BST's expected cost is 2.75**
 - An Optimal BST is not necessarily a tree whose overall height is smallest.
不一定要求树的高度最小
 - Nor can we necessarily construct an Optimal BST by always putting the key with the greatest probability at the root. (The lowest expected cost of any BST with k_5 (the greatest probability) at the root is 2.85.)
不一定将概率最大的 key 放在树根，如...

15.5 Optimal binary search trees

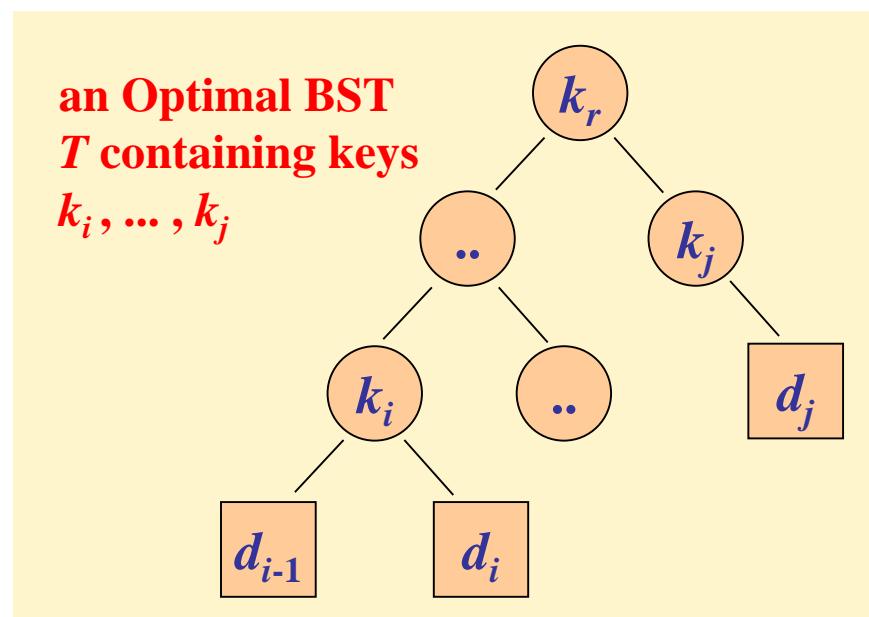
- Exhaustive checking of all possibilities fails to yield an efficient algorithm.
 - ◆ ALS, RodCut, MCM



- The # of BST with n nodes is $\Omega(4^n/n^{3/2})$ (Problem 12-4) .
- Not surprisingly, we will solve this problem with dynamic programming.

Step 1: The structure of an Optimal BST

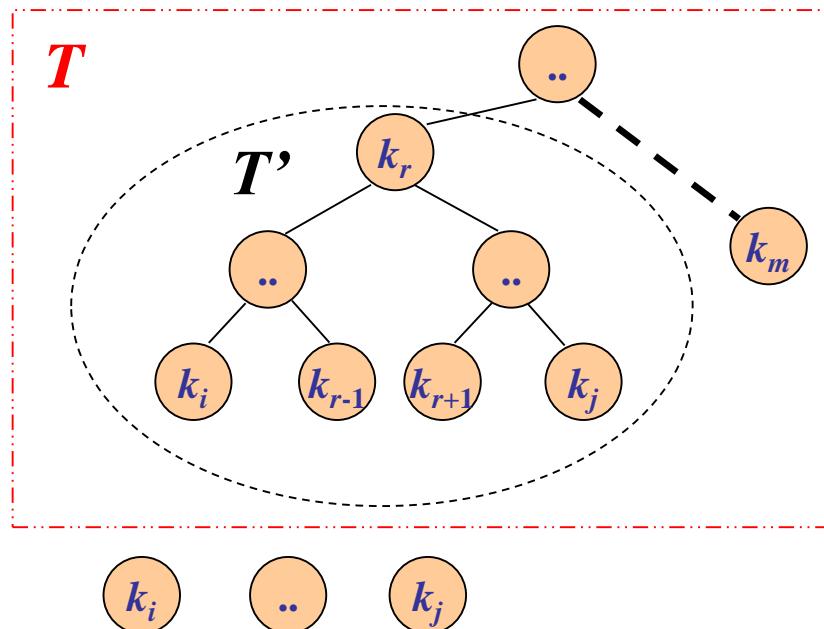
- Start with an observation about subtrees.
- Consider any subtree of a BST
 - ◆ It must contain keys in a contiguous range k_i, \dots, k_j , for some $1 \leq i \leq j \leq n$.
 - ◆ In addition, the subtree must also have as its leaves the dummy keys d_{i-1}, \dots, d_j .
- Optimal substructure?



Step 1: The structure of an Optimal BST

Optimal substructure: If an Optimal BST T has a subtree T' containing keys k_i, \dots, k_j , then this subtree T' must be optimal as well for the subproblem with keys k_i, \dots, k_j and dummy keys d_{i-1}, \dots, d_j .

设 T' 为最优BST T 的一个子树， T' 包含keys k_i, \dots, k_j ，那么 T' 是子问题〔关于 keys k_i, \dots, k_j 和 dummy keys d_{i-1}, \dots, d_j 〕的最优BST



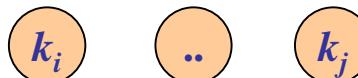
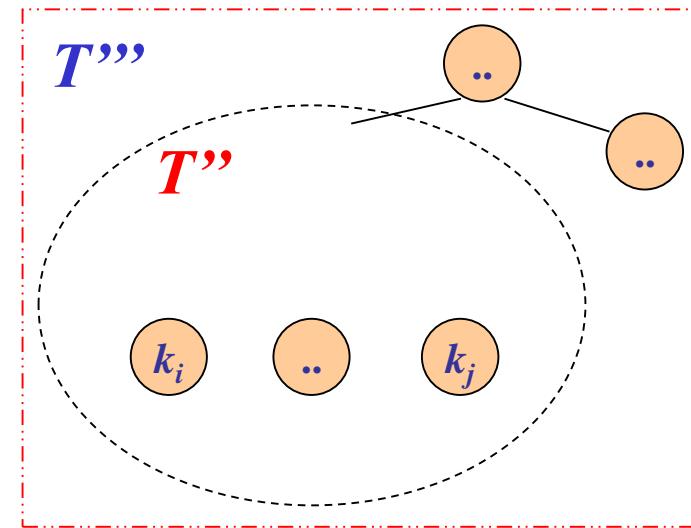
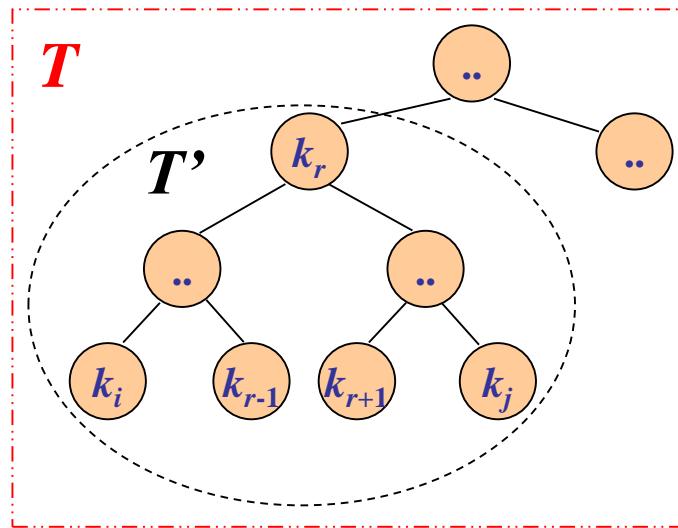
T : search tree of k_i, \dots, k_m
 T' : search tree of k_i, \dots, k_j

Optimal BST T
→ Optimal BST T'

Step 1: The structure of an Optimal BST

Idea of Proof: Cut-and-paste argument applies.

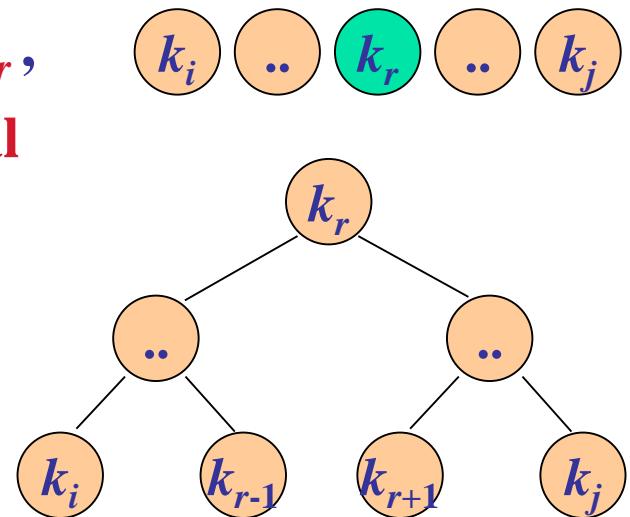
If there were a subtree T'' whose expected cost is lower than that of T' , then we could cut T' out of T and paste in T'' , resulting in a binary search tree of lower expected cost than T , thus contradicting the optimality of T .



$$E[\text{cost}(T)] = 1 + \sum_{i=1}^n \text{depth}_T(k_i) \cdot p_i + \sum_{i=0}^n \text{depth}_T(d_i) \cdot q_i$$

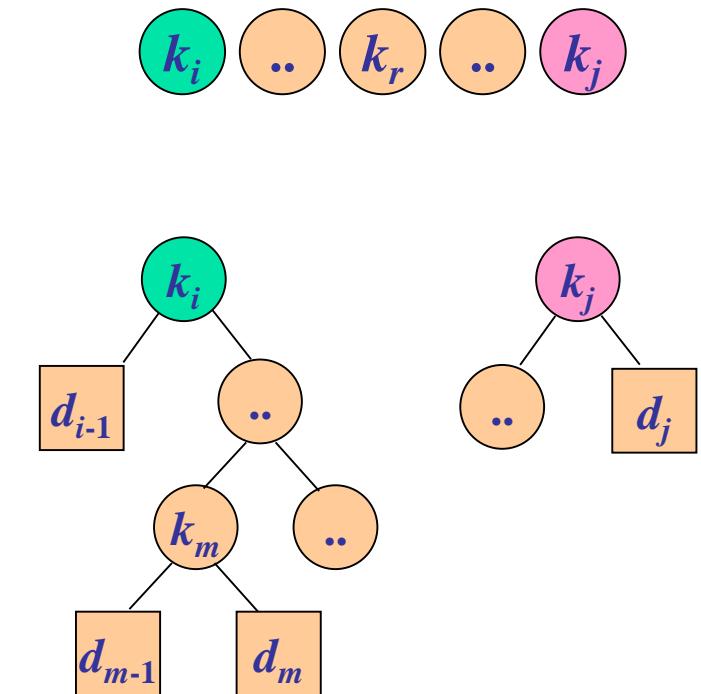
Step 1: The structure of an Optimal BST

- Using the optimal substructure, we can construct an optimal solution to the problem from optimal solutions to subproblems.
- Given keys k_i, \dots, k_j , one of these keys, say k_r ($i \leq r \leq j$), will be the root of an optimal subtree.
 - ◆ The left subtree of the root k_r will contain the keys k_i, \dots, k_{r-1} (and dummy keys d_{i-1}, \dots, d_{r-1}); the right subtree will contain the keys k_{r+1}, \dots, k_j (and dummy keys d_r, \dots, d_j).
- As long as we examine all candidate roots k_r , where $i \leq r \leq j$, and we determine all optimal BST containing k_i, \dots, k_{r-1} and those containing k_{r+1}, \dots, k_j , we will find an Optimal BST.



Step 1: The structure of an Optimal BST

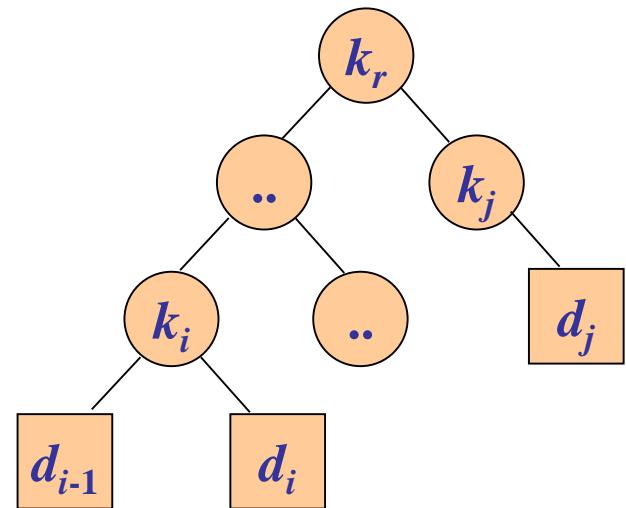
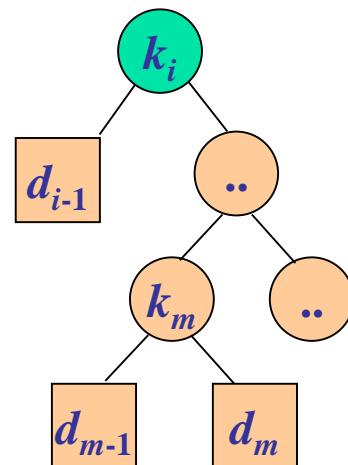
- A detail, “empty” subtrees
- Suppose that in a subtree with keys k_i, \dots, k_j ,
 - ◆ We select k_i as the root, left subtree of k_i contains no keys. Bear in mind, however, that subtrees also contain dummy keys d_{i-1} .
 - ◆ Symmetrically, if we select k_j as the root, right subtree of k_j contains the keys k_{j+1}, \dots, k_j ; this right subtree contains no actual keys, but it does contain the dummy key d_j .



Step 2: A recursive solution

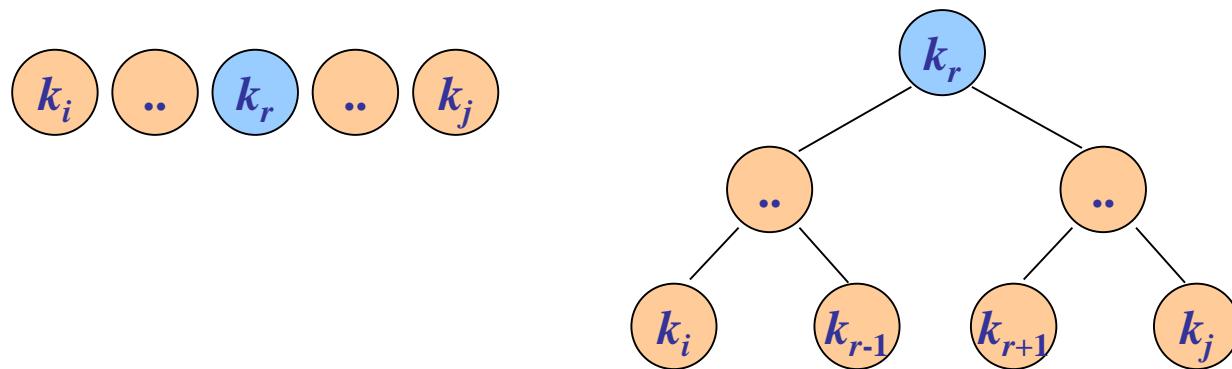
Subproblem : finding an Optimal BST containing the keys k_i, \dots, k_j , where $i \geq 1, j \leq n$, and $j \geq i-1$. (when $j = i-1$, there are no actual keys, we have just the dummy key d_{i-1} .)

- **$e[i, j]$: the expected cost of searching an Optimal BST containing the keys k_i, \dots, k_j .**
- Ultimately, wish to compute $e[1, n]$.
- when $j = i-1$, only d_{i-1} , $e[i, i-1] = q_{i-1}$.
- When $j \geq i$?



Step 2: A recursive solution

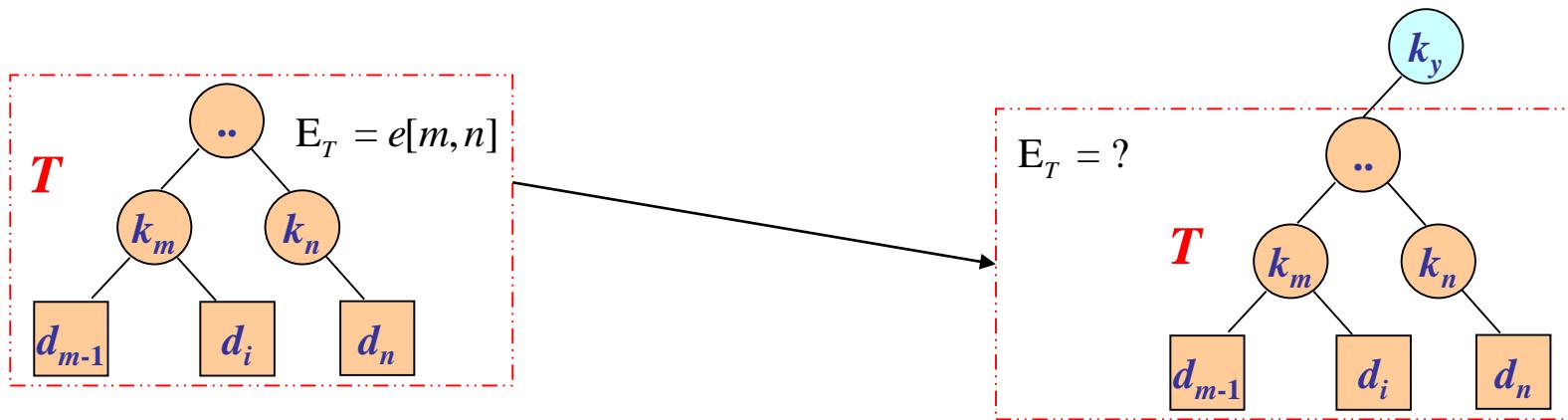
When $j \geq i$, select a root k_r from among k_i, \dots, k_j , and then make an Optimal BST with keys k_i, \dots, k_{r-1} its **left subtree** and an Optimal BST with keys k_{r+1}, \dots, k_j its **right subtree**.



Step 2: A recursive solution

What happens to the expected search cost of a subtree T when it becomes a subtree of a node?

- The depth of each node in the subtree increases by 1, the expected search cost of this subtree increases by **the sum of all the probabilities** in the subtree.



the sum of all the probabilities:

$$w[i, j] = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l \quad (15.17)$$

$$\begin{aligned}
 E_T &= \sum_{x=m}^n (\text{depth}(k_x) + 1 + 1) \cdot p_i + \sum_{x=m-1}^n (\text{depth}(d_x) + 1 + 1) \cdot q_x \\
 &= \sum_{x=m}^n (\text{depth}(k_x) + 1) \cdot p_i + \sum_{x=m-1}^n (\text{depth}(d_x) + 1) \cdot q_x + \sum_{x=m}^n p_i + \sum_{x=m-1}^n q_x \\
 &= e[m, n] + w[m, n]
 \end{aligned}$$

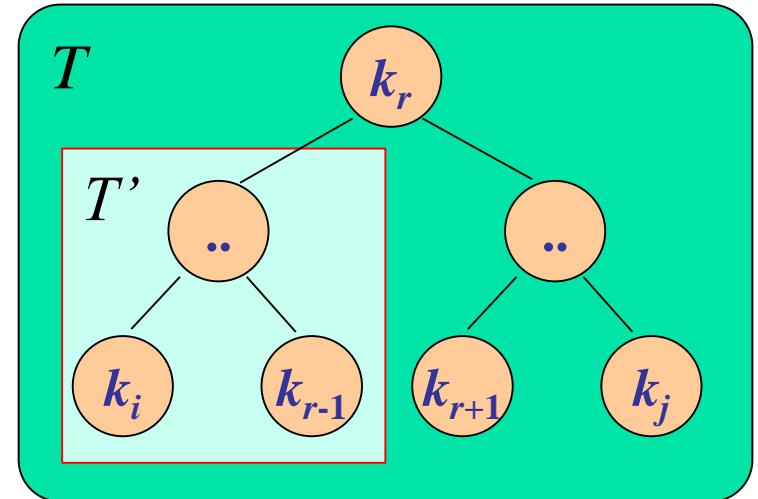
增量为 $w[m, n]$

Step 2: A recursive solution

OBST T 与 OBS-subTree T' 的关系:

if k_r is the root of an OBST containing keys k_i, \dots, k_j , we have

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



Noting that $w[i, j] = w[i, r-1] + p_r + w[r+1, j]$

$$\left(w[i, r-1] = \sum_{l=i}^{r-1} p_l + \sum_{l=i-1}^{r-1} q_l , \quad w[r+1, j] = \sum_{l=r+1}^j p_l + \sum_{l=r}^j q_l \right)$$

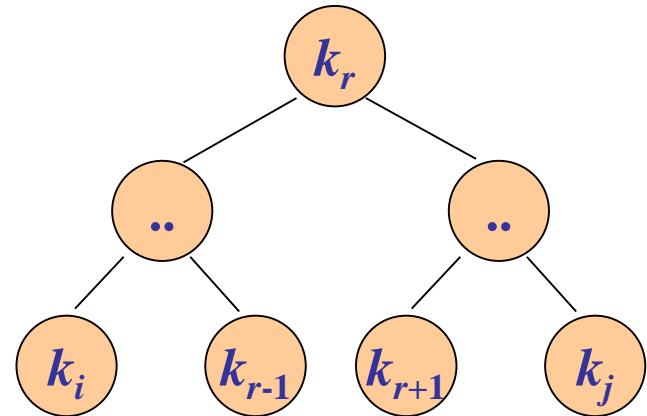
We rewrite $e[i, j]$ as

$$e[i, j] = e[i, r-1] + e[r+1, j] + w[i, j] \quad (15.18)$$

The recursive equation (15.18) assumes that we know which node k_r to use as the root, which we do not know.

Step 2: A recursive solution

- Choose k_r as the root that gives the lowest expected search cost, giving us the final recursive formulation of an OBST cost $e[i, j]$:



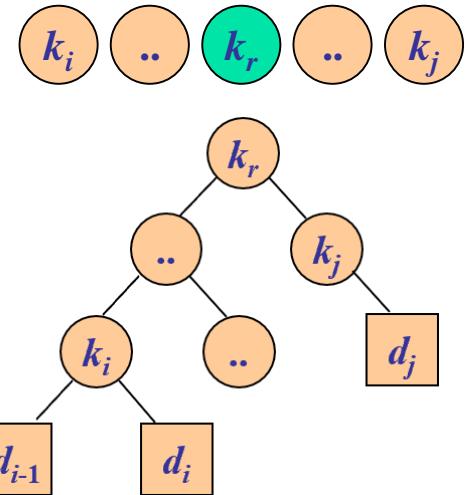
$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i - 1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & \text{if } i \leq j. \end{cases} \quad (15.19)$$

- To help us keep track of the structure of Optimal BST, define $\text{root}[i, j]$, for $1 \leq i \leq j \leq n$, to be the index r for which k_r is the root of an Optimal BST containing keys k_i, \dots, k_j .

Step 3: Computing the expected search cost

$A_i \dots A_k A_{k+1} \dots A_j$

$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i-1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & \text{if } i \leq j. \end{cases} \quad (15.19)$$



- **Similarity:** OBST and matrix-chain multiplication.
- A direct, **recursive** implementation would be as **inefficient**?
- Store the $e[i, j]$ values in a table $e[1.. n+1, 0.. n]$.
 - ◆ The first index runs to $n+1$, in order to have a subtree containing only d_n , need to compute and store $e[n+1, n]$.
 - ◆ The second index starts from 0, in order to have a subtree containing only d_0 , need to compute and store $e[1, 0]$.
- $\text{root}[i, j]$, recording the root of the subtree containing keys k_i, \dots, k_j .

Step 3: Computing the expected search cost

- Other table for efficiency.

$$e[i, j] = e[i, r-1] + e[r+1, j] + w[i, j] \quad (15.18)$$

- Rather than compute the value of $w[i, j]$ every time we are computing $e[i, j]$ —which would take $\Theta(j-i)$ additions—we store these values in a table $w[1.. n+1, 0.. n]$.

(无需每次计算 $e[i, j]$ 时都计算 $w[i, j]$, ...)

- For the base case, we compute $w[i, i-1] = q_{i-1}$ for $1 \leq i \leq n$.

- For $j \geq i$, $w[i, j] = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l = w[i, j-1] + p_j + q_j$ (15.20)

- Thus, compute the $\Theta(n^2)$ values of $w[i, j]$ in $\Theta(1)$ time each.
- Inputs: the probabilities p_1, \dots, p_n and q_0, \dots, q_n and the size n

Step 3: Computing the expected search cost

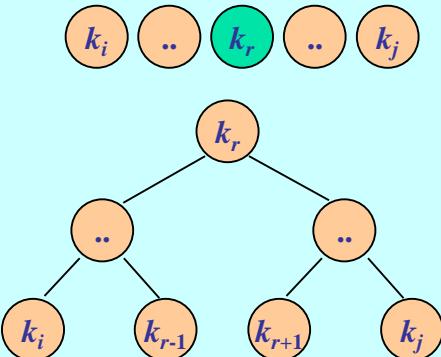
$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i-1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & \text{if } i \leq j. \end{cases} \quad (15.19)$$

$$w[i, j] = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l = w[i, j-1] + p_j + q_j \quad (15.20)$$

OBST(p, q, n)

```

1 for  $i \leftarrow 1$  to  $n+1$ 
2    $e[i, i-1] \leftarrow q_{i-1}$ 
3    $w[i, i-1] \leftarrow q_{i-1}$ 
4 for  $l \leftarrow 1$  to  $n$ 
5   for  $i \leftarrow 1$  to  $n-l+1$ 
6      $j \leftarrow i+l-1$ 
7      $e[i, j] \leftarrow \infty$ 
8      $w[i, j] \leftarrow w[i, j-1] + p_j + q_j$ 
9     for  $r \leftarrow i$  to  $j$ 
10        $t \leftarrow e[i, r-1] + e[r+1, j] + w[i, j]$ 
11       if  $t < e[i, j]$ 
12          $e[i, j] \leftarrow t$ 
13          $root[i, j] \leftarrow r$ 
14 return  $e$  and  $root$ 
```



VS

($(A_i(A_{i+1} \dots \dots A_k) (A_{k+1} \dots A_{j-1} A_j)$)

$$m[i, j] = \begin{cases} 0 & \text{if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k+1, j] + p_{i-1} p_k p_j\}, & \text{if } i < j. \end{cases} \quad (15.12)$$

MCM-DP(p)

```

1  $n \leftarrow \text{length}[p] - 1$ 
2 for  $i \leftarrow 1$  to  $n$ 
3    $m[i, i] \leftarrow 0$ 
4 for  $l \leftarrow 2$  to  $n$  //  $l$  is the chain length.
5   for  $i \leftarrow 1$  to  $n - l + 1$ 
6      $j \leftarrow i + l - 1$ 
7      $m[i, j] \leftarrow \infty$ 
8     for  $k \leftarrow i$  to  $j - 1$ 
9        $q \leftarrow m[i, k] + m[k+1, j] + p_{i-1} p_k p_j$ 
10      if  $q < m[i, j]$ 
11         $m[i, j] \leftarrow q$ 
12         $s[i, j] \leftarrow k$ 
13 return  $m$  and  $s$ 
```

Step 3: Computing the expected search cost

OBST(p, q, n)

```
1 for i←1 to n+1
2   e[i, i-1]←qi-1
3   w[i, i-1]←qi-1
4 for l←1 to n
5   for i←1 to n-l+1 // ?1
6     j←i+l-1      // ?2
7     e[i, j]←∞
8     w[i, j]←w[i, j-1]+pj+qj
9     for r←i to j
10       t←e[i, r-1]+e[r+1, j]+w[i, j]
11       if t<e[i, j]
12         e[i, j]←t
13         root[i, j]←r
14 return e and root
```

$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i-1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & \text{if } i \leq j. \end{cases} \quad (15.19)$$

$$w[i, j] = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l = w[i, j-1] + p_j + q_j \quad (15.20)$$

?1

$e[i, j]$:

l 个元素的 Opti-BST 的 cost

$i = 1, j = l,$

$i = 2, j = l+1,$

...

$i = x, j = n,$

$n-x+1=l \Rightarrow x=n-l+1$

?2

$j-i+1 = l \Rightarrow j = i+l-1$

Step 3: Computing the expected search cost

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

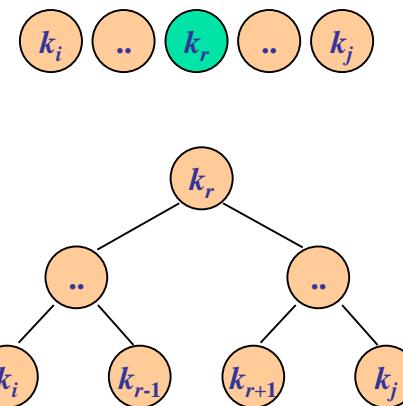
$$w(i, j) = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l = w(i, j-1) + p_j + q_j$$

```

OBST( $p, q, n$ )
1 for  $i \leftarrow 1$  to  $n+1$ 
2    $e[i, i-1] \leftarrow q_{i-1}$ 
3    $w[i, i-1] \leftarrow q_{i-1}$ 
4 for  $l \leftarrow 1$  to  $n$  // 求 $l$ 个元素的Opti-BST
5   for  $i \leftarrow 1$  to  $n-l+1$ 
6      $j \leftarrow i+l-1$ 
7      $e[i, j] \leftarrow \infty$ 
8      $w[i, j] \leftarrow w[i, j-1] + p_j + q_j$ 
9     for  $r \leftarrow i$  to  $j$ 
10        $t \leftarrow e[i, r-1] + e[r+1, j] + w[i, j]$ 
11       if  $t < e[i, j]$ 
12          $e[i, j] \leftarrow t$ 
13          $root[i, j] \leftarrow r$ 
14 return  $e$  and  $root$ 

```

Innermost for loop, in lines 9–13, tries each candidate index r to determine which key k_r to use as the root of an OBST containing keys k_i, \dots, k_j . 对包含 k_i, \dots, k_j 的最优 BST，遍历每一个 k_r 作为树根，…



Step 3: Computing the expected search cost

$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i-1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & \text{if } i \leq j. \end{cases} \quad (15.19)$$

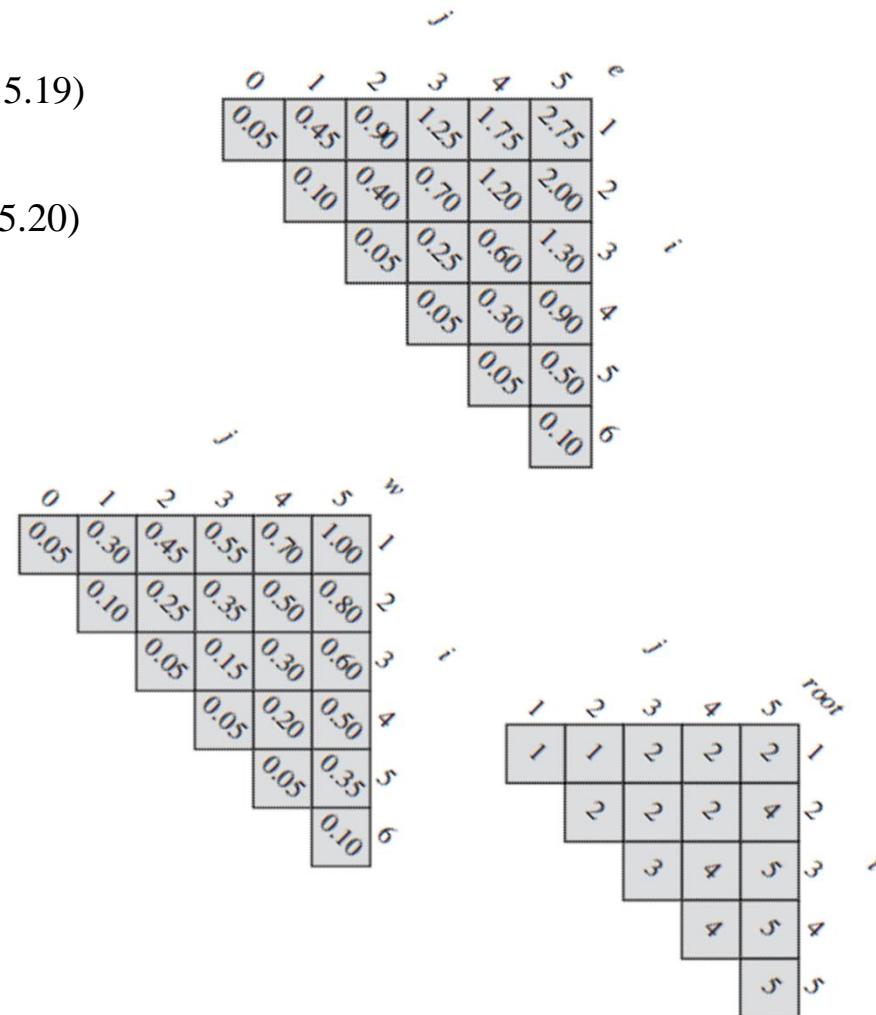
$$w[i, j] = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l = w[i, j-1] + p_j + q_j \quad (15.20)$$

OBST(p, q, n)

```

1 for i←1 to n+1
2   e[i, i-1]←qi-1
3   w[i, i-1]←qi-1
4 for l←1 to n    // 求l个元素的Opti-BST
5   for i←1 to n-l+1
6     j←i+l-1
7     e[i, j]←∞
8     w[i, j]←w[i, j-1]+pj+qj
9     for r←i to j
10       t←e[i, r-1]+e[r+1, j]+w[i, j]
11       if t<e[i, j]
12         e[i, j]←t
13         root[i, j]←r
14 return e and root

```



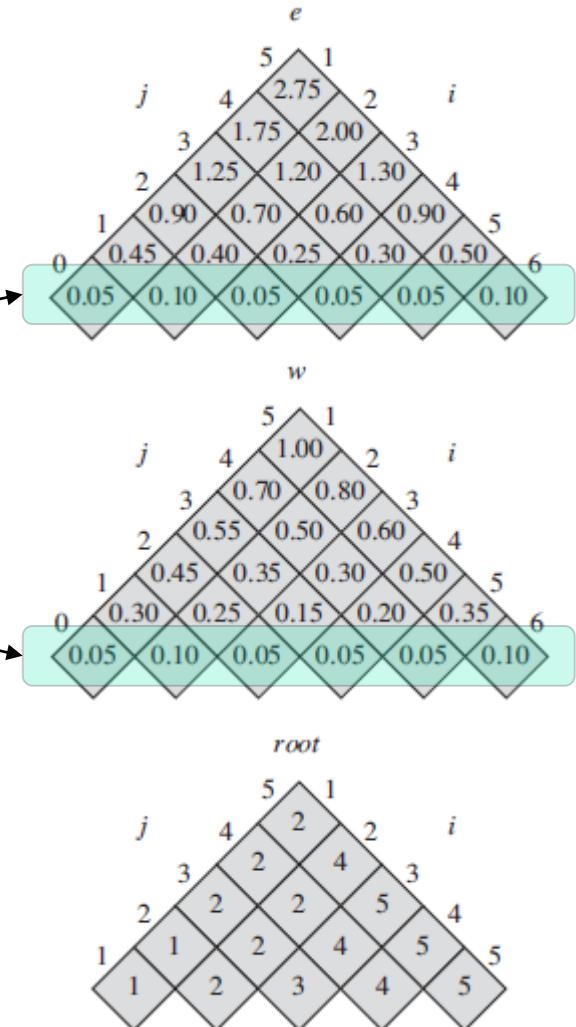
Step 3: Computing the expected search cost

$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i-1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & \text{if } i \leq j. \end{cases} \quad (15.19)$$

$$w[i, j] = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l = w[i, j-1] + p_j + q_j \quad (15.20)$$

```

OBST(p, q, n)
1 for i←1 to n+1
2   e[i, i-1]←qi-1
3   w[i, i-1]←qi-1
4 for l←1 to n // 求l个元素的Opti-BST
5   for i←1 to n-l+1
6     j←i+l-1
7     e[i, j]←∞
8     w[i, j]←w[i, j-1]+pj+qj
9     for r←i to j
10       t←e[i, r-1]+e[r+1, j]+w[i, j]
11       if t<e[i, j]
12         e[i, j]←t
13         root[i, j]←r
14 return e and root
    
```



Step 3: Computing the expected search cost

$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i-1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & \text{if } i \leq j. \end{cases} \quad (15.19)$$

$$w[i, j] = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l = w[i, j-1] + p_j + q_j \quad (15.20)$$

```
OBST(p, q, n)
1 for i←1 to n+1
2   e[i, i-1]←qi-1
3   w[i, i-1]←qi-1
4 for l←1 to n
5   for i←1 to n-l+1 // n-l+1 times
6     j←i+l-1
7     e[i, j]←∞
8     w[i, j]←w[i, j-1]+pj+qj
9     for r←i to j // j-i+1=i+l-1-i+1=l
10       t←e[i, r-1]+e[r+1, j]+w[i, j]
11       if t<e[i, j]
12         e[i, j]←t
13         root[i, j]←r
14 return e and root
```

Running times ?

Exercise-5 (in class)

$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i - 1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & \text{if } i \leq j. \end{cases} \quad (15.19)$$

$$w[i, j] = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l = w[i, j-1] + p_j + q_j \quad (15.20)$$

Based on equations (15.19) and (15.20) from the OBST,

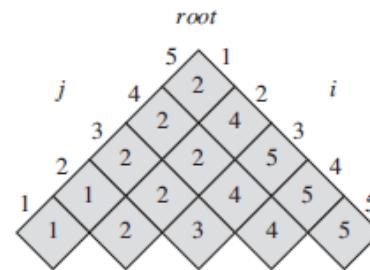
What is the **raw Recursive algorithm?**

What is the **Recursive algorithm with Memoization?**

Running time?

Exercise-6

15.5-1 Write pseudocode for the procedure CONSTRUCT-OPTIMAL-BST(root) which, given the table root , outputs the structure of an optimal binary search tree. For the example in Figure 15.8, your procedure should print out the



$k2$ is the root
 $k1$ is the left child of $k2$
 $d0$ is the left child of $k1$
 $d1$ is the right child of $k1$
 $k5$ is the right child of $k2$
 $k4$ is the left child of $k5$
 $k3$ is the left child of $k4$
 $d2$ is the left child of $k3$
 $d3$ is the right child of $k3$
 $d4$ is the right child of $k4$
 $d5$ is the right child of $k5$

Solution of Exercise-6

15.5-1

```
A(r, i, j)
1 if i=1 && j=n
2   r[i, j] is the root
3 if i=j
4   print "d"i-1 "is the left child of k"i
5   print "d"i "is the right child of k"i
6 else if r[i, j]=i
7   print "d"i-1 "is the left child of k"i
8   print "k"r[i+1, j] "is the right child of k"r[i, j]
9   A(r, i+1, j)
10 else if r[i, j]=j
11   print "k"r[i, j-1] is the left child of k"r[i, j]
12   A(r, i, j-1)
13   print "d"j "is the right child of k"j
14 else // i<r[i, j]<j
15   print "k"r[i, r[i, j]-1] "is the left child of k"r[i, j]
16   A(r, i, r[i,j]-1)
17   print "k"r[r[i, j]+1, j] "is the right child of k"r[i, j]
18   A(r, r[i, j]+1, j)
```

Big Exercises

根据一本专业书籍（如《算法导论》），建设一个翻译软件中计算机类词库（字典）的OBST。说明：只考虑英语单词作为关键字。

求解思路：

1. 统计书籍里有多少个单词 M
2. 按字母序，第 i ($1 \leq i \leq n$) 个单词在书中出现了 k_i 次
 $(k_1 + k_2 + \dots + k_n = M)$ ，其词频 $p_i = k_i / M$
3. 根据词频表，构建OBST

思考：对比一般的平衡搜索树 BBST（用中间点作为树根），比较 BBST 与 OBST 的搜索代价。

Eggs



D 生命之水

时间限制: 1000ms 内存限制: 65536kb

通过率: 162/200 (81.00%) 正确率: 162/493 (32.86%)

题目描述

经过你辛勤的浇灌和修剪，你的绿藤长势极好，甚至分出了 n 条绿枝，但最近绿藤的生长停滞了，似乎遇到了瓶颈。

你偶然间得到了生命之水，传说生命之水可以滋养万物，提供生命之力，于是你想到了你心爱的绿藤。

每当你使用生命之水滋养一条绿枝时，绿藤可以获得 x_i 的成长增益值，但是你不能同时滋养相邻的两条绿枝，这会触发生命之水的副作用，使绿藤失去生机。

现在，你想知道在不触发副作用的情况下绿藤可以获得的成长增益值最大是多少？

输入格式

第一行包含一个整数 t ，表示测试数据的数量，接下来 t 组测试数据。

每组测试数据包含两行。

第一行包含一个正整数 $n(2 \leq n \leq 10^5)$ ，含义如上。



Eggs

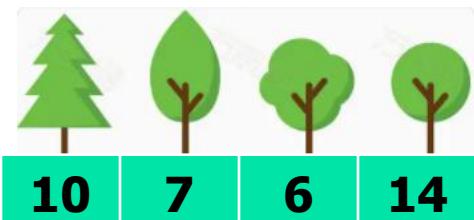
D 生命之水

输入

2
3
1 8 2
4
10 7 6 14

输出

8
24



方法一：

n 颗小树的成长值记为 $a_1, a_2, a_3, \dots, a_n$

浇灌第 $i \sim j$ 颗小树获得的最大值为 $m[i, j]$, 若浇灌 a_k , 有

$$m[i, j] = \max(m[i, k-2] + a_k + m[k+2, j]), i \leq k \leq j$$

$m[i, j] = a_i, i == j$ 时,

$m[i, j] = 0, i > j$ 时.

按题意,

空间复杂度超了
计算时时间复杂度也超

方法二：

$m[j]$ 表示浇灌 $1 \sim j$ 颗小树获得的最大值, 则

$$m[j] = \max(m[j-2] + a_j, m[j-1])$$

$m[1] = a_1$,

$m[2] = \max(a_1, a_2)$.

符合题意

Exercises

ADF WorkShop