

Dynamic Programming

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This is the augmented transcript of lectures given by Luc Devroye on the week of the 25th of January 2018 for the Honours Data Structures and Algorithms class (COMP 252, McGill University). The subject was Dynamic Programming.

THE PRINCIPLE: in dynamic programming, to find a solution of a problem of a given size, we solve all the necessary sub-problems.

Fb

1 Binomial Coefficient

We would like to compute the binomial coefficient defined as

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} = \frac{n(n-1)\cdots(n-k+1)}{k(k-1)\cdots1}$$

RAM: $2(k-1)$ multiplication
 $\Theta(k)$

DIRECT COMPUTATION: if $k < n/2$, this can be done in $2k$ multiplications. So we have RAM model complexity $\Theta(\min(k, n-k))$, since one of k or $n-k$ will be $\leq n/2$ and $\binom{n}{k} = \binom{n}{n-k}$.

RECURRENCE RELATION: the binomial coefficient $\binom{n}{k}$ is the number of ways of choosing k out of n integers. Recall the recursive formula:¹

$$\left\{ \begin{array}{l} \binom{n}{0} = \binom{n}{n} = 1 \\ \binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k} \end{array} \right. \text{ last included}$$

Using this, we can form a Pascal Triangle as shown in Figure 1. The following algorithm will, for a given element (N, K) , compute the matrix below that element, obtaining $\binom{N}{K}$.

COMPUTE-BINOMIAL-COEFFICIENT(N, K)

```

1 for n = 0 to N      // rows
2   for k = 0 to K    // columns
3     if k = 0 or k = n then  $\binom{n}{k} = 1$ 
4     else  $\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$ 

```

This algorithm has time complexity $\underline{\underline{O(NK)}}$.

Exercise 1. Improve the code to get complexity $O(K \cdot (N - K))$.

Hint: compute only a strip as shown in Figure 2.

compute all sub solutions

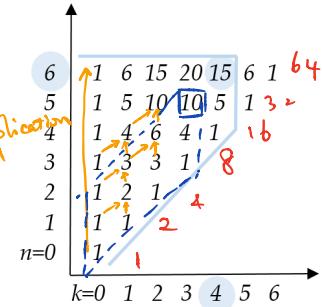


Figure 1: To compute $\binom{6}{4}$, compute all entries in the matrix below this element.

¹ Why is this true?

Proof. Fix some integer a . It is either part of the k or not.

- If the set of k numbers contains a , then for the remaining we must pick $k-1$ out of $n-1$ integers.
- If the set doesn't contain a , we must pick k out of $n-1$ integers. \square

use matrix
 $M(n, k)$

$$M[n, 0] = 1, M[n, k] = 1$$

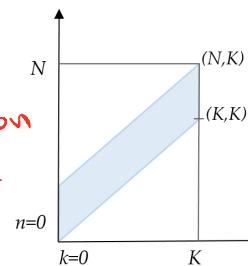


Figure 2: Hint for Exercise 1.

$n \times$ linear

Rod cutting

2	7	4	4	1	2
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price of nodes length 1, 2, 3 ... is different.

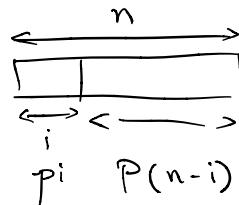
Max return?

$$\# \text{ sol.} = 2^{n-1} \text{ max cut #}$$

Recursive program.

n : rod length.

$P(n)$: optimal total return.



If $n=0$, then return 0.

else return $\max_{1 \leq i \leq n} (p_i + P(n-i))$

T_n = time comp $P(n)$

Induction. claim: $T_n = 2^n$

$$\begin{cases} T_0 = 1 \\ T_n = 1 + \underbrace{T_0}_{2^0} + \underbrace{T_1}_{2^1} + \dots + \underbrace{T_{n-1}}_{2^{n-1}} \stackrel{n}{=} 2^n \end{cases} \checkmark$$

price
 $p_j = \{2, 7, 4, \dots\}$

Dynamic program.

for $i=0$ to n do:

if $i=0$ then $P[i] = 0$
else $P[i] = \max_{1 \leq j \leq i} (p_j + P[i-j]) \rightarrow z_i$

$$\sum_{i=0}^n z_i = \Theta(n^2) \leq \Theta(2^n)$$

ex. length = 9
 $P[9] = \max(2+P[8], 7+P[8], 4+P[8], \dots)$
 $\{ \text{if } T - P[i]. \text{ iterating logic} \}$

$$\left\{ \begin{array}{l} P(1) = 2 \\ P(2) = P(1) + 2 = 4 \\ = P(2) = 4 \\ P(3) = \{ P(2) * P(1) \\ = P(2) + P(2)_{i-j} \} \end{array} \right. \quad \text{base case}$$

Fb 2 Partitions of $\{1, \dots, n\}$ into k non-empty sets

Given $\{1, \dots, n\}$, we want to compute the number of possible partitions of these integers into k non-empty sets. Indeed, observe the recursion:

$$P(\{1, \dots, n\}, k) = \underbrace{P(\{1, \dots, n-1\}, k)}_{\text{element } n \text{ joins an existing set}} + \underbrace{P(\{1, \dots, n-1\}, k-1)}_{\text{starts a new set by itself}}$$

$$P_{n,k} = k \cdot P_{n-1,k} + P_{n-1,k-1}$$

We see that we can use exactly the same matrix-filling algorithm as the last section with only minor changes. Note that here, in the initialization, $P_{n,n} = P_{n,1} = 1$.

The complexity is therefore the same as Section 1: $O(nk)$.

	1	63	301	350	140	21	1
6	1	31	90	65	15	1	
5	1	15	25	10	1		
4	1	7	6	1			
3	1	3	1				
2	1	1					
$n=1$	1						

Figure 3: We compute, for example, 140 via: $140 = 5 \times 15 + 65$

✓ 3 Travelling Salesman Problem (TSP)

INPUT: Matrix of distances $dist[i,j]$ between all cities $1 \leq i, j \leq n$.

OBJECTIVE: Find the tour through all cities of smallest total length.

3.1 Naive Algorithm

$\frac{(n-1)!}{2}$ double count

Consider all $(n-1)!$ permutations of $\{2, \dots, n\}$ and compute the lengths of all tours that start and end at "1".

With this approach, we obtain complexity $T(n) = n \times (n-1)! = n!$ where n comes from summing the lengths and $(n-1)!$ is the number of tours.

3.2 Dynamic Programming Approach: Finding $L[1, S, j]$

Definition 2. Consider $L(1, S, j)$, the length of the shortest path between 1 and j via all of S , where $S \subseteq \{1, \dots, n\}$ is the set of all cities with 1 and j removed, i.e., $S = \{1, \dots, n\} - \{1\} - \{j\}$.

In this algorithm, we will store $L[1, S, j]$ for all j and subsets S in a large matrix. Figure 5 illustrates line 5 of the algorithm. Once this matrix is found, computing the TSP tour will only require $\Theta(n)$ time.

TSP-DP-ALGORITHM($dist[i,j] \forall i,j$)

```

1 for all  $j \neq 1$ :  $L[1, \emptyset, j] = dist[1, j]$  // initialization
2 for  $k = 1$  to  $n-2$  //  $k$ : size of  $S \{1, \dots, n\}$ 
3   for all  $S$  with  $|S| = k$ ,  $S \subseteq \{2, \dots, n\}$ 
4     for all  $j \neq S$  //  $j$  before  $1$ 
5        $L[1, S, j] = \min_{\ell \in S} (L[1, S - \{\ell\}, \ell] + dist[\ell, j])$ 
    
```

If $|S|=0$ then $L[1, j] = dist[1, j]$

base case

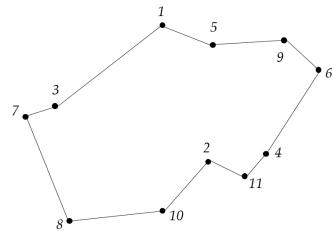


Figure 4: Example of a tour through $n = 11$ cities.

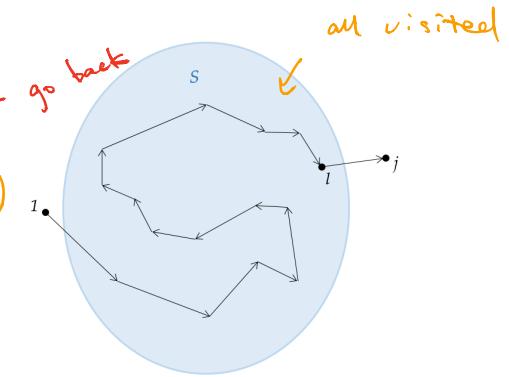


Figure 5: Illustration of innermost algorithm loop: recall that

$$S = \{1, \dots, n\} - \{1\} - \{j\}$$

The length of the path between city 1 and city j is equal to the length of the shortest path between 1 and some city $\ell \in S$, plus the distance between ℓ and j . To find the shortest path between 1 and j , we must choose the city ℓ which minimizes this quantity.

ℓ
 $S (0001001101\dots)$ number
 $S - \{\ell\} (0001001101\dots) \# - 2^d$

known.

① as start $\{1, 2, 3, 4, \dots, n\}$.
 for $j = 2, 3, 4, \dots, n$: $L[1, \phi, j] = \text{dist}[1, j]$; [find end] $(n-1)$

for $k = 1 \sim n-2$
 for each $s \subseteq \{2, \dots, n\}$ with size k , $\binom{n-2}{k}$ $L[1, \phi, k] = \text{dist}[1, l]$
 $L[1, \phi, k] = \min_{l \in s} (L[1, s - \{l\}, k] + \text{dist}[l, j])$

$k=1 \binom{n-2}{1} L[1, \underbrace{\{1, n-2\}}, j] = \min (L[1, s - \{l\}, 1] + \text{dist}[l, j])$
 $n-2 \uparrow L[1, s, j] \rightarrow \text{matrix, } \min \text{. min.}$

$k=2 \binom{n-2}{2} L[1, \underbrace{\{s\}=2}, j] = \min (L[1, s - \{l\}, 2] + \text{dist}[l, j])$
 $\binom{n-2}{2} \uparrow L[1, s, j] \rightarrow \text{matrix, } \min \text{ 2 迭 1.}$

$k=3 \binom{n-2}{3} L[1, \underbrace{\{s\}=3}, j] = \min (L[1, s - \{l\}, 3] + \text{dist}[l, j])$
 $\binom{n-2}{1} + \binom{n-2}{2} \times 2 + \binom{n-2}{3} \times 3 + \binom{n-2}{4} \times 4 + \dots + \binom{n-2}{n-2} \times (n-2)$

$= (n-2) 2^{n-3} \times (n-1) \times n \quad n^2$

$(n-2) \times \binom{2}{1} \times n \times (n-1) \stackrel{?}{=} \binom{n}{2} \times \binom{2}{1}$

$\frac{(n-2)!}{2!(n-4)!} \times n \times (n-1) = \frac{n!}{2!(n-4)!} \quad n \geq 0$

$(n-2) 2^{n-3} + (n-1) \cancel{\times} = 2^{n-3} (n^3 - 3n^2 + 2n) \leq 2^{n-3} 3n^3 = C_1 n^2$
 $\Rightarrow = (n-2) 2^{n-3} + n-1 \leq n 2^{n-3} + n$
 $n^3 2^{n-3} \quad n^2$
 $= n(2^{n-3} + 1)$
 $\leq n 2^{n-2} \quad \checkmark$

$$P(S, j) = \arg \min_{\ell \in S} \{ \dots \}$$

To analyze the time complexity, we must consider three parts:

- all subsets of S are considered at most once:² contribution $\leq 2^n$
- for every set S , we consider at most n values of j : contribution $\leq n$
- for each (S, j) pair, we calculate a minimum over at most n choices of ℓ : contribution $\leq n$

So the total complexity of the dynamic programming algorithm to find L , the length of the shortest path between 1 and any other city j , is $T(n) \leq n^2 \cdot 2^n$ in the RAM model. Note that this is $\ll n!$. Storage of order $\Theta(n \cdot 2^n)$ is needed.

3.3 Finding the TSP Tour

Once we have $L[1, S, j]$ for all $S \subseteq \{1, \dots, n\}$ and $j \in S$, the length of the TSP tour is, as shown in Figure 6

$$TSPLen = \min_{j \neq 1} (L[1, S, j] + \underbrace{dist[1, j]}_{\text{cost } n})$$

Last step

where we can read all $L[1, S, j]$ off our table. The time complexity of this search (over $n - 1$ possibilities of j) is just $\Theta(n)$, which is added to the time needed to build L . Therefore the total algorithm time complexity remains $T(n) = O(n^2 2^n)$.

Exercise 3. Use additional storage so that you also output the optimal tour as a sequence of vertices.³

4 Knapsack Problem

INPUT: Items of sizes $x_1, \dots, x_N \in \mathbb{Z}$; and a knapsack of size $K \in \mathbb{Z}$.

OBJECTIVE: Determine if there exists a subset $S \subseteq \{1, \dots, N\}$ for the input sizes such that $\sum_{i \in S} x_i = K$.

Notation 4. Define the matrices $P[n, k]$ and $S[n, k]$ respectively as

$$P[n, k] = \begin{cases} 1 & \text{if KNAPSACK } (\{x_1, \dots, x_n\}, k) \text{ has a solution} \\ 0 & \text{else} \end{cases}$$

$$S[n, k] = \begin{cases} 1 & \text{if } x_n \text{ belongs to a solution of } P[n, k] \\ 0 & \text{else} \end{cases}$$

but it's not

such that P tells us, for a knapsack of capacity k , whether or not there exists a solution with elements up to element n ; and S tells us, given a knapsack of capacity k , if we should select element n or not.

² Recall that a set of size n has 2^n subsets

$$S = \{3, 5, 7\}$$

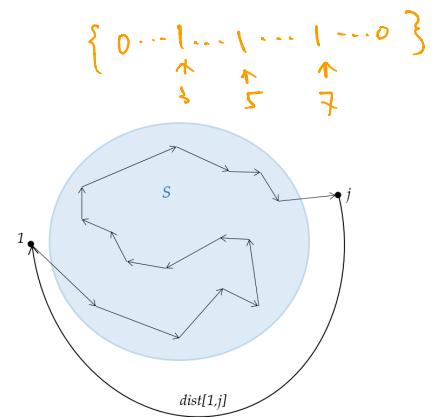
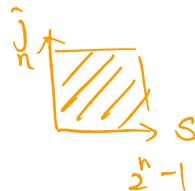


Figure 6: Completing the TSP tour.



³ HINT: think about pointers from j to the last vertex in S visited for $L[1, S, j]$.

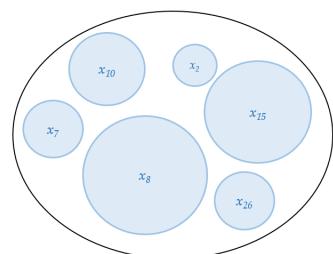
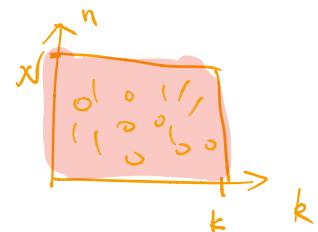
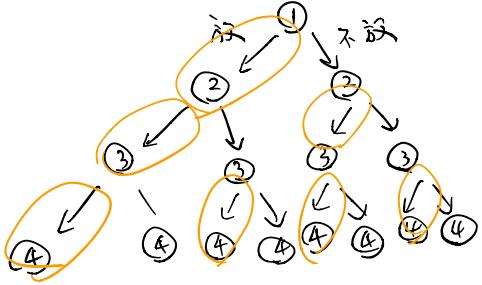


Figure 7: Example of a solution: a set of items $x_i, i \in S \subseteq \{1, \dots, N\}$, which fill a knapsack of size K

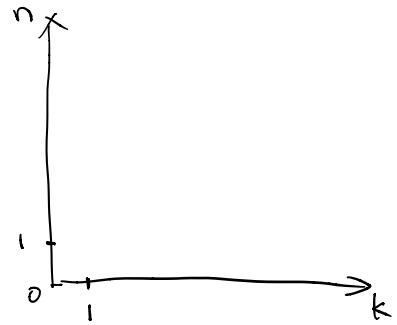


灰色問題：



$n=0$ 放东西. $K=0 : N \ size \uparrow P = 0$

$n=1$ 有 1 个 $K=0 : N \ size \uparrow$



size 4.1 Solving for possibility matrix $P[N, K]$

To find the matrix P , we will be computing all values $P[i, j]$ for $i \leq n$ and $j \leq k$. As defined in the inputs, let the knapsack size be K and number of elements be N .

KNAPSACK-COMPUTE- $P(N, K)$ ← build matrix

```

1  for n = 0 to N
2    for k = 0 to K
3      if n = k = 0 then P[n, k] = 1
4      base case { else if n = 0, k > 0 then P[0, k] = 0 // no elements
5      else if n > 0, k = 0 then P[n, 0] = 1 // can choose the
           . . . // empty set  $S$  to fill a knapsack of capacity 0
6      else
7        P[n, k] =  $\begin{cases} P[n - 1, k] & \text{if } x_n > k \\ 1 & \text{if } x_n = k \\ \max(P[n - 1, k], P[n - 1, k - x_n]) & \text{if } x_n < k \end{cases}$ 

```

This algorithm has complexity $T(N) = \Theta(NK)$.

4.2 Computing a solution via $S[N, K]$

We can easily modify the previous algorithm⁴ (by simply adding a few lines) to also fill the matrix S , which tells us which items $x_i, i \in S \subseteq \{1, \dots, N\}$ are used to fill the knapsack.

KNAPSACK-ALSO-COMPUTE- $S(N, K)$

```

1  for n = 0 to N
2    for k = 0 to K
3      if n = k = 0 then P[n, k] = 1, S[n, k] = 0
4      else if n = 0, k > 0 then P[0, k] = 0, S[0, k] = 0
5      else if n > 0, k = 0 then P[n, 0] = 1, S[n, 0] = 0
           // we choose the empty set so no elements are selected
6      else
7        if  $x_n > k$  then P[n, k] = P[n - 1, k], S[n, k] = 0
           // don't select this element
8        else if  $x_n = k$  then P[n, k] = 1, S[n, k] = 1
           // we add this element to the solution
9        else if  $x_n < k$ 
10       P[n, k] = max(P[n - 1, k], P[n - 1, k - x_n])
11       if P[n, k] = 0 then S[n, k] = 0
           // neither was possible
12       else if P[n - 1, k - x_n] = 1 then S[n, k] = 1
           // choosing to put in  $x_n$  worked
13       else S[n, k] = 0 // solution without  $x_n$  worked

```

$x_n > k$: the element x_n is greater than the remaining capacity: no solution

$x_n = k$: there definitely exists a solution containing x_n

$x_n < k$: we either (1st option) don't put x_n into the set or (2nd option) put it in

⁴ The previous algorithm gave us whether it is possible to solve the knapsack problem for N elements x_1, \dots, x_N and a knapsack of size K .

This will have the same time complexity as the previous algorithm.

Exercise 5. Write a program that also outputs a knapsack solution if it exists. Assume $P[N, K] = 1$ and all entries $P[n, k]$ and $S[n, k]$ for $n \leq N, k \leq K$ are known.

Exercise 6. Modify the dynamic program for the case that there is an unlimited supply of items of each of the sizes x_1, \dots, x_n .

5 Assignment Problem

INPUT: An $n \times n$ matrix, as shown in figure 8, which describes matches $\delta_{ij} \geq 0$.

OBJECTIVE: Find the permutation $(\sigma_1, \dots, \sigma_n)$ of $(1, \dots, n)$ that maximizes $\sum_{i=1}^n \delta_{i\sigma_i}$

Naively, this can be done in time $O(n! \cdot n)$. We will use dynamic programming to reduce this, by computing sub-solutions for all sub-matrices $A \times B$ where $A, B \subseteq \{1, \dots, n\}$, as shown in Figure 8.

Definition 7. Denote the best assignment for this sub-matrix $A \times B$ as $\text{BEST}[A, B]$. The goal is to compute $\text{BEST}[A, B]$ for all sets A and B such that $|A| = |B| = k$, for k running from 1 to n .

FIND-BEST-ASSIGNMENT($\delta_{ij} \forall i, j$)

```

1  for  $k = 0$  to  $n$ 
2    for all sets  $A, B \subseteq \{1, \dots, n\}$  with  $|A| = |B| = k$  // of size  $k$ 
3      if  $k = 0$  then  $\text{BEST}(\emptyset, \emptyset) = 0$ 
4      else
5         $\text{BEST}[A, B] = \min_{x \in A, y \in B} (\delta_{xy} + \text{BEST}[A - \{x\}, B - \{y\}])$ 

```

For the time complexity of this algorithm, we again consider different parts of the algorithm. We consider all sets A, B of size k , so since there are 2^k subsets of size k and we consider k running up to n , we can upper bound this by $2^n \cdot 2^n$. In the else loop, we compute the minimum over all $x \in A$ and $y \in B$ which both have size k : we can therefore upper bound this cost by n^2 .

We therefore have total cost $T(n) \leq 2^n \cdot 2^n \cdot n^2 = O(n^2 4^n)$.

6 Job Scheduling $n \cdot 2^n$

INPUT: jobs J_1, \dots, J_n requiring times τ_1, \dots, τ_n to complete; and $c_i(t) = \text{cost incurred if job } i \text{ ends at time } t$.

OBJECTIVE: Find a permutation $(\sigma_1, \dots, \sigma_n)$ of $(1, \dots, n)$ such that the total cost is minimal if jobs are sequenced as job J_{σ_1} first, then job J_{σ_2} , etc.

$n!$ worse case

Solution (4).

```

1   $k \leftarrow K$ 
2  for  $n = N$  down to 1
3    if  $S[n, k] = 1$ 
4      output  $x_n$ 
5       $k \leftarrow k - x_n$ 

```

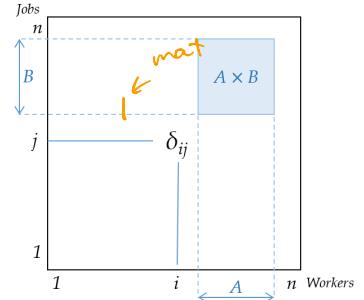


Figure 8: The assignment matrix can be thought of as matching n workers to n jobs. Entries δ_{ij} represent how well worker i and job j 'match'.

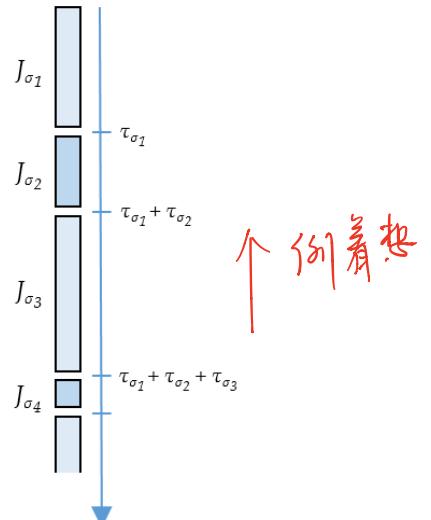


Figure 9: Job scheduling problem visualization

所以是全层，本节是
 $n \times k \Rightarrow n \times k \binom{n}{k}$
 用 min 来选择 同种 choose
 minimize 为一个值。

Ex. $\hat{C}(s) = \min_{|S|=3} (C(s_{\{j\}}) + C_i(\sum T_j))$
 - 共有 $\binom{n}{3}$ 种，其中 \leftarrow 由 $C(s)$ 定
 上一个 for $C(s)$ $|S|=2$ 中 $\binom{n}{2}$
 写遍历， $\binom{n}{2}$ 中 $\{2, 3\}$
 $\{3, 2\}$ 只有
 一个会是
 下面

$$\begin{array}{ll} k=1 & n \\ k=2 & n \times \min(n \times 2) \\ & \frac{n!}{(n-k)!} \quad \frac{n(n-1)}{2} \end{array}$$

$$\begin{array}{cccccc} 1 & 2 & 3 & 4 & & \\ (2, 13, 14, 23, 24, 34) & \xrightarrow{\binom{4}{2} \binom{2}{1}} & \binom{n}{2} \binom{2}{1} \\ (123, 124, 234, 134) & \xrightarrow{\binom{4}{3} \times \binom{3}{2}} & \binom{n}{3} \binom{3}{2} \\ 4+(123) & 2+(134) & 3+(124) & 1+(234) & \xrightarrow{\binom{n}{4} \binom{4}{3}} & \end{array}$$

$$\binom{n}{2} \binom{2}{1} = \frac{n!}{2!(n-2)!} \cdot \frac{2!}{1!} = \frac{n!}{(n-2)!} \quad \binom{n}{3} \binom{3}{2} = \frac{n!}{3!(n-3)!} \cdot \frac{3!}{2!} = \frac{n!}{(n-3)! \cdot 2!}$$

$$\frac{n!}{(n-4)! \cdot 3!} + \frac{n!}{(n-3)! \cdot 4!} \dots \frac{n!}{(n-n)! \cdot (n-1)!} = n$$

$$n + n(n-1) + n(n-1)(n-2) \cdot \frac{1}{2!} + \dots + n(n-1)(n-2) \cdot \frac{1}{2!} + \dots + n(n-1) \cdot \frac{n(n-1)}{n-1} + \dots$$

$$\dots + n(n-1) + n \cdot \binom{n-1}{2} + \binom{n-1}{3} \cdot n + \dots + \binom{n-1}{n-2} + \dots + \binom{n-1}{n-1}$$

$$= n \cdot \left(\binom{n-1}{1} + \binom{n-1}{2} + \dots + \binom{n-1}{n-1} \right)$$

DYNAMIC PROGRAMMING 6

This total cost will be

$$Cost = c_{\sigma_1}(T_{\sigma_1}) + c_{\sigma_2}(T_{\sigma_1} + T_{\sigma_2}) + \cdots + c_{\sigma_n}(T_{\sigma_1} + \cdots + T_{\sigma_n})$$

For our dynamic programming algorithm, let $S \subseteq \{1, \dots, n\}$ be a subset of the jobs and set $C(S)$ be the optimal cost for that subset.

JOB-SCHEDULING($J_i, \tau_i, c_i(t) \forall i$)

$|S|_1 \rightarrow$ for $k = 0$ to N \star \leftarrow Total cost
 $|S|_2 \rightarrow$ for all $S \subseteq \{1, \dots, n\}$ of size k do: ? \leftarrow Total cost
 3 $|S| \rightarrow C(S) = \min_{i \in S} \left(C(S - \{i\}) + c_i \left(\sum_{j \in S} \tau_j \right) \right)$ \leftarrow Total cost

By a similar analysis as in Section 5, this algorithm has complexity

$$T(n) = O(n \cdot 2^n). \quad \sum_{k=1}^n \binom{n}{k} \cdot k \leq n \cdot 2^n$$

7 Longest Common Subsequence

The next two sections (7 and 8) are adapted from Ruo Yu Tao and Sitong Chen's 2018 scribed notes⁵, with a few adjustments.

INPUT: two ordered sequences: x_1, \dots, x_n and y_1, \dots, y_m where all elements x_i and y_j come from a finite alphabet A , (for example $\{0, 1\}$ or $\{A, C, G, T\}$).

OBJECTIVE: Find the longest common subsequence: that is, the longest sequences $1 \leq i_1 < i_2 < \dots < i_k \leq n$, $1 \leq j_1 < \dots < j_k \leq m$ such that $x_{i_1} = y_{j_1}, \dots, x_{i_k} = y_{j_k}$. See Figure 10 for an example.

Let the matrix element $L[i, j]$ be the length of the longest common subsequence of x_1, \dots, x_i and y_1, \dots, y_j . The following dynamic program will fill the matrix L .

COMPUTE-LCS-LENGTH(n, m)

```

1   for all  $i = 0$  to  $n$ 
2       for all  $j = 0$  to  $m$ 
3           if  $i = 0$  or  $j = 0$  then  $L[i, j] = 0$     // initialize
4           else
5                $L[i, j] = \begin{cases} 1 + L[i - 1, j - 1] & \text{if } \\ \max(L[i - 1, j], L[i, j - 1]) & \text{if } \end{cases}$ 

```

The entry $L[n, m]$ will be the length of the Longest Common Subsequence for the given input x_1, \dots, x_n and y_1, \dots, y_m . The construction of this matrix L takes time $\Theta(nm)$.

We can now define an algorithm that takes in the matrix defined above and returns the longest common subsequence:

$$\begin{aligned}
 S &\Rightarrow 2^n < n! \\
 &= 1 + n + \binom{n}{2} + \dots + \binom{n}{n} = 2^n \\
 &= (1+1)^n \leq Q_1 \cdot \text{large job}
 \end{aligned}$$

Storage	#	
	0	0 0 0 0 0 0 0 0
$n \times 2$	1	0 0 0 0 0 0 0 1
	2	0 0 0 0 0 0 0 0
	.	.
	.	.
	-	.
	-	.
	-	.
	$2^n - 1$	1 1 1 1 1 1 1 1

⁵ R. Y. Tao and S. Chen. *Dynamic Programming* (2). McGill University, January 2018

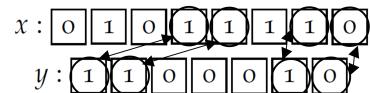
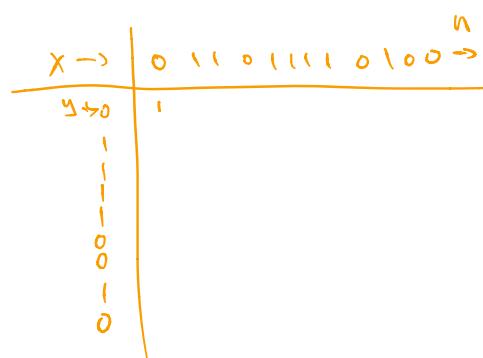
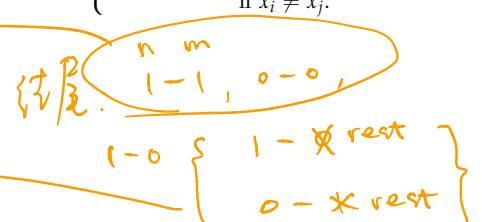


Figure 10: Example of two sequences with longest common subsequence
 1110.

The last element in the matrix L would be:

$$L[i, j] = \begin{cases} 1 + L[i - 1, j - 1] & \text{if } x_i = x_j, \\ \max(L[i - 1, j], L[i, j - 1]) & \text{if } x_i \neq x_j. \end{cases}$$



COMPUTE-LCS

```

1 let  $i = n, j = m, r =$  empty list for results.
// We start at the cell of the last row of the last column.
2 while  $i \geq 0$  and  $j \geq 0$  // repeat this until out of matrix bounds
3   if  $x_i = y_j$ 
4     append  $x_i$  to  $r$ .
5      $i = i - 1, j = j - 1$  // go North West (NW) one cell
6   else // else, if  $x_i \neq y_j$ , choose the maximum between the
        // the numbers in the West and North cells.
7     if  $L[i - 1, j] \geq L[i, j - 1]$  then  $i = i - 1$ 
8     else  $j = j - 1$ 
9 return  $r$ 

```

This algorithm is illustrated in Figure 7, by the circles and arrows.

8 Optimal Binary Search Tree

Once again, this section is adapted from Ruo Yu Tao and Sitong Chen's 2018 scribed notes⁶.

8.1 Background

Suppose that we are designing a compiler for a language, in which there are n syntactic keywords with corresponding semantics. For each occurrence of a keyword, we would want to perform a lookup operation by building a static binary search tree with n syntactic words as keys and their semantics as data stored in corresponding nodes. For the efficiency of the compiler, we would like to design a static binary search tree that minimizes total search time.⁷

We know that for a balanced tree, we can ensure an $O(\log n)$ search time per occurrence; however those syntactic words can appear with different frequencies. For example, if a frequently used word such as "if" is placed at the leave of this tree, it will greatly increase the total search time and hence the compiling time, vice versa. Therefore, given that we know the frequency of each key word appearing, we would like to organize a binary search tree in a way that minimizes the overall number of nodes visited. Such a tree is known as an optimal binary search tree. Moreover, it may be intuitive to consider a tree with smallest depth and key words of highest frequency at the root as an optimal binary search tree. However neither condition is necessary.⁸

match at $\textcircled{1}$
 ↗ match to $\textcircled{2}$.

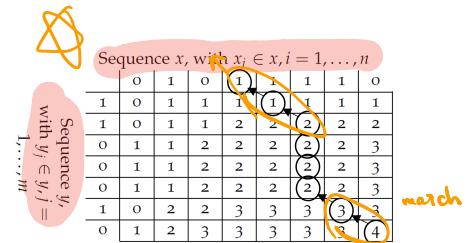
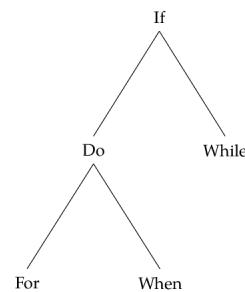


Figure 11: Example of two sequences with a longest common subsequence of length 4.

⁶ R. Y. Tao and S. Chen. *Dynamic Programming (2)*. McGill University, January 2018

⁷

Key words	Frequency(w)
If	w_1
Do	w_2
While	w_3
For	w_4
When	w_5
...	...
Keyword _n	w_n



⁸ T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein. *Introduction to Algorithms*. MIT Press, 3rd edition, 1989

8.2 Algorithm

INPUT: sorted (key, weight) pairs $(k_1, w_1), \dots, (k_n, w_n)$, where the weights denote frequency or popularity.

OBJECTIVE: construct a binary search tree (BST) of minimal total weight $\sum_{i=1}^n d_i w_i$, where key k_i is at depth d_i .

Here $d_i = 1$ if k_i is the root.

Observe that any subtree of a binary search tree contains keys in a contiguous range $k_i \dots k_j$, for some $1 \leq i \leq j \leq n$. If an optimal binary search tree 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 key $k_i \dots k_j$. If there were a subtree T'' whose expected cost of searching is lower than that of T' , then we could replace T' with T'' .

Therefore, given a binary tree with keys $k_i \dots k_j$, say k_r where $i \leq r \leq j$ is the root of an optimal subtree, then the left subtree contains keys $k_i \dots k_{r-1}$, while the right subtree contains keys $k_{r+1} \dots k_j$. If we check all possible candidate roots k_r , and identify the left and right subtree with minimum cost of searching, we are guaranteed to find an optimal binary search tree.

Definition 8. *tree*

- Let $C[i, j] = \sum_{k=i}^j w_k d_k$ denote the optimal cost for the tree containing $(k_i, w_i), \dots, (k_j, w_j)$.
- Let $W[i, j] = \sum_{k=i}^j w_k$ denote the total weight of all keywords with indices i, \dots, j .

We will compute $C[1, n]$ by computing all $C[i, j]$ for $1 \leq i \leq j \leq n$.

Computing W

From Definition 8, we have that

$$W[i, j] = \begin{cases} w_i & \text{if } i = j, \\ W[i, j-1] + w_i & \text{if } i < j. \end{cases}$$

COMPUTE- $W((k_i, w_i) \forall i)$ *自己 charge 1.*

```

1  for i = 1 to n: W[i, i] = w_i    // initialization
2  for k = 1 to n - 1
3      for i = 1 to n
4          if i + k ≤ n then W[i, i + k] = W[i, i + k - 1] + w_{i+k}
5  return W

```

COMPUTE- W has time complexity $T(n) = \Theta(n^2)$.

Computing C

If $k_r, r \in [i, j]$ is the root of the optimal subtree for the tree containing k_i to k_j , we can consider subtrees as in Figure 8.2 where the left and right subtrees are both optimal and respectively contain $(k_i, w_i), \dots, (k_{r-1}, w_{r-1})$ and $(k_{r+1}, w_{r+1}), \dots, (k_j, w_j)$. Taking the root that yields minimum total cost thus yields the following formula

$$C[i, j] = \min_{i \leq r \leq j} \left\{ \begin{array}{l} C[i, r - 1] + W[i, r - 1] \\ + C[r + 1, j] + W[r + 1, j] \\ + w_r \end{array} \right\}$$

which we can rewrite using $W[i, j] = W[i, r - 1] + W[r + 1, j] + w_r$, to

$$C[i, j] = \min_{i \leq r \leq j} (C[i, r - 1] + C[r + 1, j] + W[i, j])$$

where we have $C[i, j] = 0$ if $i = j$.

Having computed the matrix W in time $\Theta(n^2)$, we can now find C :

COMPUTE-C((k_i, w_i) $\forall i$)

```

1  for  $i = 1$  to  $n$ :  $C[i, i] = w_i$ 
2  for sizeofSubtree = 2 to  $n$ 
3    for  $i = 1$  to  $n$ 
4       $j = i + \text{sizeofSubtree} - 1$ 
5      if  $j \leq n$ 
6         $\text{root } \leftarrow C[i, j] = \min_{i \leq r \leq j} (C[i, r - 1] + C[r + 1, j] + W[i, j])$ 
7         $\text{root}[i, j] = \text{one of the } r's \text{ that minimizes } C[i, j]$ 
8  return  $C, \text{root}$ 
```

COMPUTE-C has time complexity $T(n) = \Theta(n^3)$, i.e., the algorithm takes time $\Theta(n^3)$ in total.

Remark 9. Knuth⁹ has shown that there are always roots of an optimal subtree such that $\text{root}[i, j - 1] \leq \text{root}[i, j] \leq \text{root}[i + 1, j]$ for all $1 \leq i < j \leq n$. Hence we can reduce the running time of COMPUTE-C to $\Theta(n^2)$ by replacing the innermost for loop **for** $r = i$ **to** j with **for** $r = \text{root}[i, j - 1]$ **to** $\text{root}[i + 1, j]$.

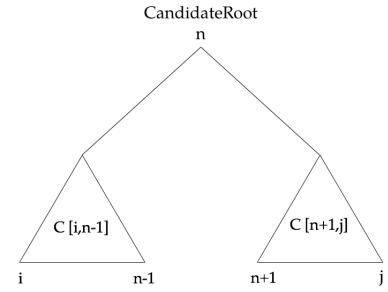


Figure 12: The above is a tree view of our recursive formula for computing total cost of searching given a keyword is chosen as the root.

⁹ D. E. Knuth. *The Art of Computer Programming*, volume 3. Addison-Wesley, 1998

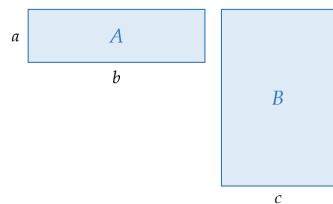


Figure 13: The number of operations needed to multiply matrices A and B of sizes $a \times b$ and $b \times c$ is $a \cdot b \cdot c$.

9 Matrix Multiplication

INPUT: matrices M_1, M_2, \dots, M_n of dimensions $r_1 \times c_1, r_2 \times c_2, \dots, r_n \times c_n$. r_i stands for the number of rows and c_i the number of columns. For the matrix multiplication to make sense, we require $c_1 = r_2, c_2 = r_3, \dots, c_{n-1} = r_n$.

OBJECTIVE: compute $M_1 \times M_2 \times \dots \times M_n$ using standard matrix multiplication, such that the total number of operations is smallest in the RAM model.

For the algorithm, we store the following subproblems:

Definition 10.

- Let $C[i, j]$ be the optimal number of operations for multiplying $M_i \times \cdots \times M_j$, $1 \leq i \leq j \leq n$. 从 i 到 j 之间，矩阵乘法的 # of operations.
- Let $B[i, j]$ be the index of best split when multiplying $M_i \times \cdots \times M_j$, say ℓ where $i \leq \ell \leq j$, so that we first do $M_i \times \cdots \times M_\ell$, then $M_{\ell+1} \times \cdots \times M_j$, and then $(M_i \times \cdots \times M_\ell) \times (M_{\ell+1} \times \cdots \times M_j)$. $B[i, j]$ is needed if we want to output the best schedule.

MATRIX-MULTIPLY($M_i \forall i$) base case 自己自己。

```

1  for  $i = 1$  to  $n$  do  $C[i, i] = 0$  // initialization: multiplying no
   ~~~~~ // matrices takes no operations
2  for  $k = 1$  to  $n - 1$  // iterate over the number of matrices to be
3     $j = i + k$  // multiplied together
4    if  $j \leq n$  then //  $j$  can't go over the number of matrices
5       $C[i, j] = \min_{i \leq \ell \leq j}$  (C[i, \ell] + C[\ell + 1, j] + r_i r_{\ell+1} c_j)
      // find the index of best split for  $M_i \times \cdots \times M_j$ 
6       $B[i, j] = \arg \min_{i \leq \ell \leq j}$  (C[i, \ell] + C[\ell + 1, j] + r_i r_{\ell+1} c_j)
      write down index
      place should split

```

The term in red on line 5, $r_i r_{\ell+1} c_j$, comes from the fact that this line is splitting $M_i \times \cdots \times M_j$ into

$$\underbrace{(M_i \times \cdots \times M_\ell)}_{r_i \times r_{\ell+1} \text{ matrix}} \times \underbrace{(M_{\ell+1} \times \cdots \times M_j)}_{r_{\ell+1} \times c_j \text{ matrix}}$$

and counting the total number of operations needed to get the answer. $C[i, \ell]$ and $C[\ell + 1, j]$ respectively count the number of operations needed to perform $M_i \times \cdots \times M_\ell$ and $M_{\ell+1} \times \cdots \times M_j$. The middle multiplication requires $r_i r_{\ell+1} c_j$ operations, as explained in Figure 13.

Exercise 11. The tree view of this algorithm is shown in Figure 14. Given the $B[\cdot, \cdot]$ matrix, write an algorithm to construct this optimal tree.

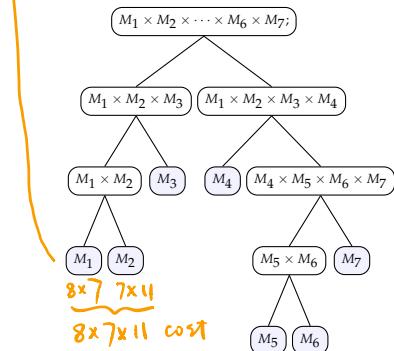


Figure 14: Tree view of the matrix multiplication algorithm.

References

- T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein. *Introduction to Algorithms*. MIT Press, 3rd edition, 1989.
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