

# 演算法

# Algorithm

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# Disclaimer

本文「演算法」為台灣研究所考試入學的「演算法」考科使用，內容主要參考洪捷先生的演算法參考書 [1]，以及 wjungle 網友在 PTT 論壇上提供的演算法筆記 [2]。

本文作者為 TZU-CHUN HSU，本文及其 L<sup>A</sup>T<sub>E</sub>X 相關程式碼採用 MIT 協議，更多內容請訪問作者之 GITHUB 分頁 [Oscarshu0719](#)。

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# 1 Overview

1. 本文頁碼標記依照實體書 [1] 的頁碼。

2. TKB 筆記 [2] 章節頁碼：

Chapter	Page No.	Importance
1	1	★★★★
2	13	★★★★
3	18	★★★★★
4	34	★★★★★
5	43	★★★
6	48	★★★
7	×	★
8	×	★★★

3. 省略第 7 章。

Dynamic Programming algorithms		
Problem	Time complexity	Space complexity
Making change	$O(kn)$	$O(n)$
Fractional Knapsack problem	$\Theta(n \log n)$	$O(n)$
0/1 Knapsack problem (DP)	$O(n2^{\log W})$	$O(n2^{\log W})$
0/1 Knapsack problem (Branch-and-Bound)	$O(2^n)$	
Longest Common Subsequence (LCS)	$O(mn)$	$O(mn)$
Longest Increasing Subsequence (LIS)	$O(n^2)$	$O(n^2)$
Longest Common Substring	$O(mn)$	$O(mn)$
Minimum Edit Distance	$O(mn)$	$O(mn)$
Matrix-chain Multiplication	$O(n^3)$	$O(n^2)$
Traveling Salesperson problem	$\Theta(n^2 2^n)$	$O(n2^n)$
Optimal Binary Search Tree (OBST)	$\Theta(n^3)$	$\Theta(n^2)$

Graph algorithms		
Problem	Time complexity	Remark
Depth-First Search (DFS)	$O( V  +  E )$	
Kosaraju's	$O( V  +  E )$	
Kruskal's	$O( E  \log  V )$	
Prim's (Adjacency matrix)	$O( V ^2)$	
Prim's (Adjacency list)	$O( V  E )$	
Prim's (Min-Heap, Adjacency list)	$O( E  \log  V )$	
Prim's (Fibonacci heap, Adjacency list)	$O( E  +  V  \log  V )$	
Sollin's (Borůvka's)	$O( E  \log  V )$	
Dijkstra's (Min-heap)	$\Theta(( E  +  V ) \log  V )$	Greedy, no negative edges or cycles
Dijkstra's (Fibonacci-heap)	$\Theta( E  +  V  \log  V )$	
Bellman-Ford	$O( V  E )$	DP
Floyd-Warshall	$\Theta( V ^3)$	DP, no negative cycles
Johnson's	$\Theta( V  E  +  V ^2 \log  V )$	No negative cycles
Ford-Fulkerson	$O( E  f^* )$	Greedy, $f^*$ 為最大流
Edmond-Karp	$O( V  E ^2)$	
Push-relabel	$O( V ^2 E )$	

## 2 Summary

### 1. Theorem (89) Longest Common Subsequence (LCS):

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

- $c[0 \cdots \text{Length}(X)][0 \cdots \text{Length}(Y)]$ ,  $c[0, 0]$  表示空字串，並初始化第一行及第一列為 0。
- 字符不同時，標示左邊或上面較大值方向，數值相同時預設  $\uparrow$ ；字符相同時標示  $\nwarrow$ 。

### 2. Theorem (94) Longest Common Substring:

$$c[i, j] = \begin{cases} 0 & , i = 0 \vee j = 0 \vee x_i \neq y_j \\ c[i - 1, j - 1] + 1 & , x_i = y_j \end{cases} \quad (2)$$

- $c[0 \cdots \text{Length}(X)][0 \cdots \text{Length}(Y)]$ ,  $c[0, 0]$  表示空字串，並初始化第一行及第一列為 0。

### 3. Theorem (94) Minimum Edit Distance:

$$c[i, j] = \min \begin{cases} c[i - 1, j] + 1 & , a_i \neq b_j \\ c[i, j - 1] + 1 & , a_i \neq b_j \\ c[i - 1, j - 1] + 1 & , a_i \neq b_j \\ c[i - 1, j - 1] & , a_i = b_j \end{cases} \quad (3)$$

- 各情況依序表示刪除  $\uparrow$ 、插入  $\leftarrow$ 、替換  $\nwarrow$  以及匹配  $\searrow^2$ 。
- $c[0 \cdots \text{Length}(X)][0 \cdots \text{Length}(Y)]$ ,  $c[0, 0]$  表示空字串，並初始化第  $i$  行為  $i$  並標示  $\uparrow$ ，第  $j$  列為  $j$  並標示  $\leftarrow$ 。
- 字符不同時，標示左邊（刪除）、上面（插入）與左上（替換）較小值方向；字符相同時標示  $\searrow^2$ 。

### 4. Theorem (100) Matrix-chain Multiplication:

- $$m[i, j] = \begin{cases} 0 & , i = j \\ \min_{i \leq k \leq j-1} \{m[i, k] + m[k+1, j] + p_{i-1}p_kp_j\} & , i < j \end{cases} \quad (4)$$

- $p[0 \cdots \text{Number}(\text{Matrices})]$ , 存入矩陣大小。
- $m[1 \cdots \text{Number}(\text{Matrices})][1 \cdots \text{Number}(\text{Matrices})]$ , 初始化對角線上元素為 0。
- $s[1 \cdots \text{Number}(\text{Matrices}) - 1][2 \cdots \text{Number}(\text{Matrices})]$ ,  $s[i, j]$  存入  $m[i, j]$  中最小值對應的  $k$ 。
- 理解:  $m[i, k]$  為拆分的前部分,  $m[k+1, j]$  為拆分的後部分,  $p_{i-1}p_kp_j$  為前後部分相乘。

### 5. Theorem (111) Optimal Binary Search Tree (OBST):

- $$e[i, j] = \begin{cases} q_{i-1} & , j = i - 1 \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w[i, j]\} & , i \leq j \end{cases} \quad (5)$$
  
 $w[i, j] = w[i, j-1] + p_j + q_j$

其中,  $p_j$  為 key (內部節點) 機率,  $q_j$  為 dummy key (外部節點) 機率。

- $w[1 \cdots \text{Number}(\text{Key}) + 1][0 \cdots \text{Number}(\text{Key})]$ , 初始化對角線上元素  $w[j+1, j]$  為  $q_j$ 。
- $e[1 \cdots \text{Number}(\text{Key}) + 1][0 \cdots \text{Number}(\text{Key})]$ , 初始化對角線上元素  $e[j+1, j]$  為  $q_j$ 。
- $r[1 \cdots \text{Number}(\text{Key})][1 \cdots \text{Number}(\text{Key})]$ ,  $r[i, j]$  存入  $e[i, j]$  中最小值對應的  $r$ 。
- 理解:  $e[i, r-1]$  為左子樹,  $e[r+1, j]$  為右子樹,  $w[i, j]$  為節點權重和, 因為計算 cost 時是節點階層加一。

### 6. Theorem (171, 178, 183, 193, 195) Shortest path:

- Floyd-Warshall: sparse 時, 也不能提升性能。
- Johnson's 在 sparse 時, 性能較 Floyd-Warshall 好; Reweight 後圖上所有邊權重皆  $> 0$ , 且最短路徑與原圖相同。
- Bellman-Ford:

$$D[v, k] = \min\{D[v, k-1], \min_{(u,v) \in E} \{D[u, k-1] + wt(u, v)\}\} \quad (6)$$

- Floyd-Warshall:

$$D^k[i, j] = \min\{D^{k-1}[i, j], D^{k-1}[i, k] + D^{k-1}[k, j]\} \quad (7)$$

7. **Theorem ()** Minimum vertex cover (tree):

$$V(v) = \min\{1 + \sum\{V(c), \forall c \in v.child\}, \\ \text{Length}\{v.child\} + \sum\{V(g), \forall c \in v.child \forall g \in c.child\}\} \quad (8)$$

8. **Theorem ()** Max-cut:

- NPC。
- 若所有邊權重皆負，則可乘上  $-1$ ，變為 Min-cut。
- 若為平面圖，可轉換為 Chinese Postman Problem（若為無向圖，即 Euler circuit，若為有向圖，則為 NPC）。

9. **Theorem (363)** Maximal points:

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1: function MAXIMALPOINTS(Point [] points)
2:   s :=  $\emptyset$ 
3:   Sort points by x-coordinate in ascend order.
4:   max_y :=  $-\infty$ 
5:   for i := n to 1 do
6:     if points[i].y > max_y then
7:       Add points[i] to s.
8:       max_y := points[i].y
9:     end if
10:  end for
11:  return s
12: end function

```

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10. **Theorem (262, 265, 285)**

- 所有 NP 問題都能多項式時間 reduce 到 NP-Hard。
- 證明 NPC: 問題屬於 NP; 已知 NPC 可以多項式時間 reduce 到該問題，即證明該問題是 NP-Hard。
- 如果可以證明 **lower bound of worst case** of NPC problems is polynomial, 則  $P = NP$ 。

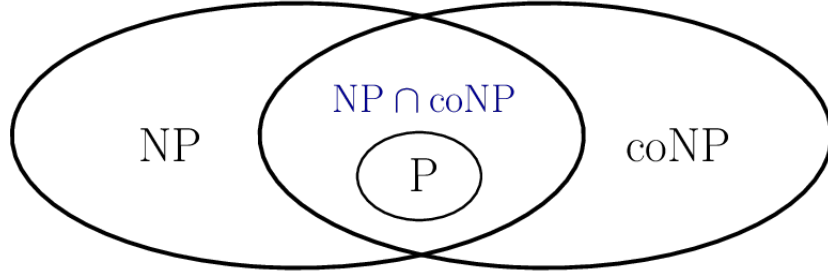


图 1: Relationship between NP and CO-NP.

#### 11. Theorem ()

- **(FALSE)** For two functions  $f(n)$  and  $g(n)$ , either  $f(n) = O(g(n))$  or  $f(n) = \Omega(g(n))$ .

Counterexample:

$$\begin{aligned} f(n) &= \begin{cases} 1, & \text{if } n = 2k \\ 0, & \text{if } n = 2k + 1 \end{cases} \\ g(n) &= \begin{cases} 0, & \text{if } n = 2k \\ 1, & \text{if } n = 2k + 1 \end{cases} \end{aligned} \tag{9}$$

- For any uniform cost RAM program  $T(n) = \Omega(S(n))$ , where  $S(n)$  is the space an algorithm uses for an input of size  $n$ .
- The capacity of each edge of a flow network can be floating-point, and it can be solved by linear programming.
- A flow network of multiple sources can be reduced to a single source.
- **(FALSE)** The value of any flow of a flow network is bounded by the capacity of only at most  $O(n)$  cuts.
- 2-coloring:  $O(n^2)$ , 3-coloring, 4-coloring: superpolynomial.
- Weighted-union heuristic: Append the **smaller** list onto the **longer** list, with ties broken arbitrarily.



## References

- [1] 洪捷. 演算法—名校攻略秘笈. 鼎茂圖書出版股份有限公司, 9 edition, 2017.
- [2] wjungle@ptt. 演算法 @tkb 筆記. <https://drive.google.com/file/d/0B8-2o6L73Q2VVmNWQk9DY3hsUm8/view?usp=sharing>, 2017.

