

Design by Induction

(Based on [Manber 1989])

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Introduction

- It is **not** necessary to design the steps required to solve a problem **from scratch**.
- It is sufficient to guarantee the following:
 - It is possible to solve one small instance or a few small instances of the problem. (**base case**)
 - A solution to every problem/instance can be constructed from solutions to smaller problems/instances. (**inductive step**)

Evaluating Polynomials

Problem

Given a sequence of real numbers $a_n, a_{n-1}, \dots, a_1, a_0$, and a real number x , compute the value of the polynomial

$$P_n(x) = a_n x^n + a_{n-1} x^{n-1} + \dots + a_1 x + a_0.$$

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Motivation: different approaches to the inductive step may result in algorithms of very different time complexities.

Evaluating Polynomials (cont.)

Let $P_{n-1}(x) = a_{n-1}x^{n-1} + \dots + a_1x + a_0$.

Induction hypothesis (first attempt)

We know how to evaluate a polynomial represented by the input a_{n-1}, \dots, a_1, a_0 , at the point x , i.e., we know how to compute $P_{n-1}(x)$.

$P_n(x) = a_nx^n + P_{n-1}(x)$.

Evaluating Polynomials (cont.)

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$P_n(x) = a_nx^n + P_{n-1}(x)$.


Number of multiplications:

$$n + (n - 1) + \dots + 2 + 1 = \frac{n(n + 1)}{2}.$$

Evaluating Polynomials (cont.)

Induction hypothesis (second attempt)


We know how to compute $P_{n-1}(x)$, and we know how to compute x^{n-1} .

 $P_n(x) = a_n x(x^{n-1}) + P_{n-1}(x).$

Evaluating Polynomials (cont.)

Induction hypothesis (second attempt)

We know how to compute $P_{n-1}(x)$, and we know how to compute x^{n-1} .

 $P_n(x) = a_n x(x^{n-1}) + P_{n-1}(x).$

 Number of multiplications: $2n - 1$.

Evaluating Polynomials (cont.)


Let $P'_{n-1}(x) = a_n x^{n-1} + a_{n-1} x^{n-2} + \cdots + a_1$.

Induction hypothesis (final attempt)

We know how to evaluate a polynomial represented by the coefficients $a_n, a_{n-1}, \cdots, a_1$, at the point x , i.e., we know how to compute $P'_{n-1}(x)$.

$P_n(x) = P'_n(x) = P'_{n-1}(x) \cdot x + a_0$.

Evaluating Polynomials (cont.)

 More generally,

$$\begin{cases} P'_0(x) = a_n \\ P'_i(x) = P'_{i-1}(x) \cdot x + a_{n-i}, \text{ for } 1 \leq i \leq n \end{cases}$$

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🌐 Number of multiplications: n .

Evaluating Polynomials (cont.)

Algorithm Polynomial_Evaluation (\bar{a}, x);

begin

$P := a_n$;

for $i := 1$ **to** n **do**

$P := x * P + a_{n-i}$

end

This algorithm is known as *Horner's rule*.

Maximal Induced Subgraph

Problem

Given an undirected graph $G = (V, E)$ and an integer k , find an induced subgraph $H = (U, F)$ of G of maximum size such that all vertices of H have degree $\geq k$ (in H), or conclude that no such induced subgraph exists.

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Design Idea: in the inductive step, we try to **remove one vertex** (that cannot possibly be part of the solution) to get a smaller instance.

Maximal Induced Subgraph (cont.)

 Recursive:

Algorithm Max_Ind_Subgraph (G, k);

begin

if the degree of every vertex of $G \geq k$ **then**

 Max_Ind_Subgraph := G ;

else let v be a vertex of G with degree $< k$;

 Max_Ind_Subgraph := Max_Ind_Subgraph($G - v, k$);

end

Maximal Induced Subgraph (cont.)

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🌐 Iterative:

Algorithm Max_Ind_Subgraph (G, k);

begin

while the degree of some vertex v of $G < k$ **do**

$G := G - v$;

 Max_Ind_Subgraph := G ;

end

One-to-One Mapping

Problem

Given a finite set A and a mapping f from A to itself, find a subset $S \subseteq A$ with the maximum number of elements, such that

- (1) the function f maps every element of S to another element of S (i.e., f maps S into itself), and
- (2) no two elements of S are mapped to the same element (i.e., f is one-to-one when restricted to S).

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An element that is not mapped to may be removed.

One-to-One Mapping (cont.)

```
Algorithm Mapping ( $f, n$ );  
begin  
   $S := A$ ;  
  for  $j := 1$  to  $n$  do  $c[j] := 0$ ;  
  for  $j := 1$  to  $n$  do increment  $c[f[j]]$ ;  
  for  $j := 1$  to  $n$  do  
    if  $c[j] = 0$  then put  $j$  in Queue;  
  while Queue not empty do  
    remove  $i$  from the top of Queue;  
     $S := S - \{i\}$ ;  
    decrement  $c[f[i]]$ ;  
    if  $c[f[i]] = 0$  then put  $f[i]$  in Queue  
end
```

Problem

Given an $n \times n$ adjacency matrix, determine whether there exists an i (the “celebrity”) such that all the entries in the i -th column (except for the ii -th entry) are 1, and all the entries in the i -th row (except for the ii -th entry) are 0.

Note: A celebrity corresponds to a **sink** of the directed graph.

Note: Every directed graph has **at most one** sink.

Celebrity

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Motivation: the trivial solution has a time complexity of $O(n^2)$. Can we do better, in $O(n)$?

To achieve $O(n)$ time, we must reduce the problem size by at least one in constant time.

Celebrity (cont.)

Basic idea: check whether i knows j .

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The $O(n)$ algorithm proceeds in two stages:

- 🌐 Eliminate a node every round until only one is left.
- 🌐 Check whether the remaining one is truly a celebrity.

Celebrity (cont.)

Algorithm Celebrity (*Know*);

begin

$i := 1;$

$j := 2;$

$next := 3;$

while $next \leq n + 1$ **do**

if $Know[i, j]$ **then** $i := next$

else $j := next;$

$next := next + 1;$

if $i = n + 1$ **then** $candidate := j$

else $candidate := i;$

Celebrity (cont.)

```
wrong := false;  
k := 1;  
Know[candidate, candidate] := false;  
while not wrong and  $k \leq n$  do  
    if Know[candidate, k] then wrong := true;  
    if not Know[k, candidate] then  
        if candidate  $\neq k$  then wrong := true;  
        k := k + 1;  
if not wrong then celebrity := candidate  
    else celebrity := 0;  
end
```

The Skyline Problem

Problem

Given the exact locations and shapes of several rectangular buildings in a city, draw the skyline (in two dimension) of these buildings, eliminating hidden lines.

Motivation: different approaches to the inductive step may result in algorithms of very different time complexities.

The Skyline Problem

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Given the exact locations and shapes of several rectangular buildings in a city, draw the skyline (in two dimension) of these buildings, eliminating hidden lines.

Motivation: different approaches to the inductive step may result in algorithms of very different time complexities.

Compare: adding buildings one by one to an existing skyline vs. merging two skylines of about the same size

The Skyline Problem

- Adding one building at a time:

$$\begin{cases} T(1) = O(1) \\ T(n) = T(n-1) + O(n), n \geq 2 \end{cases}$$

Time complexity: $O(n^2)$.

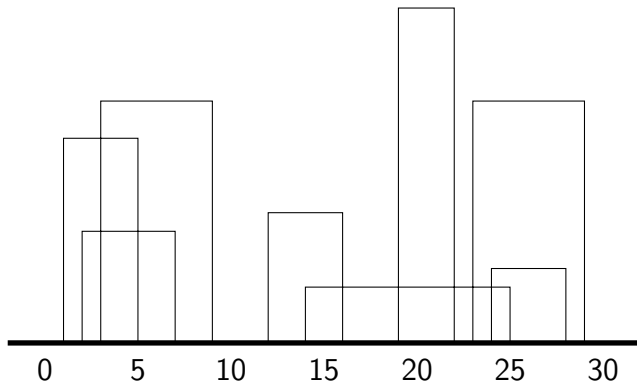
- Merging two skylines every round:

$$\begin{cases} T(1) = O(1) \\ T(n) = 2T(\frac{n}{2}) + O(n), n \geq 2 \end{cases}$$

Time complexity: $O(n \log n)$.

Representation of a Skyline

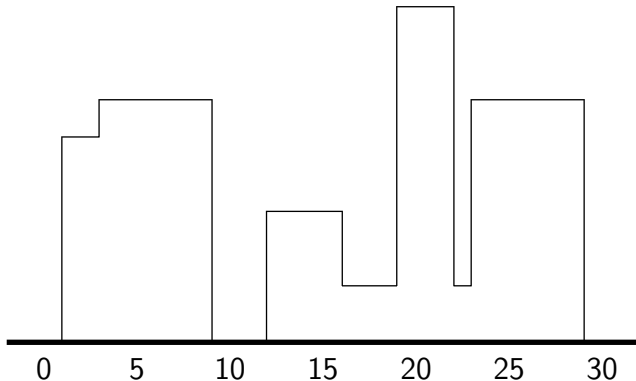
Input: $(1, \mathbf{11}, 5)$, $(2, \mathbf{6}, 7)$, $(3, \mathbf{13}, 9)$, $(12, \mathbf{7}, 16)$, $(14, \mathbf{3}, 25)$, $(19, \mathbf{18}, 22)$,
 $(23, \mathbf{13}, 29)$, and $(24, \mathbf{4}, 28)$.



Source: adapted from [Manber 1989, Figure 5.5(a)].

Representation of a Skyline (cont.)

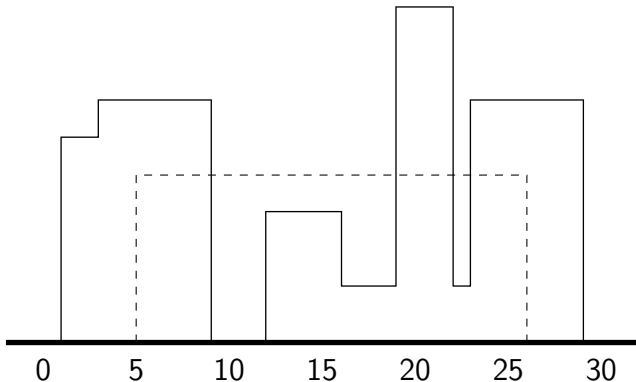
Representation: (1,11,3,13,9,0,12,7,16,3,19,18,22,3,23,13,29).



Source: adapted from [Manber 1989, Figure 5.5(b)].

Adding a Building

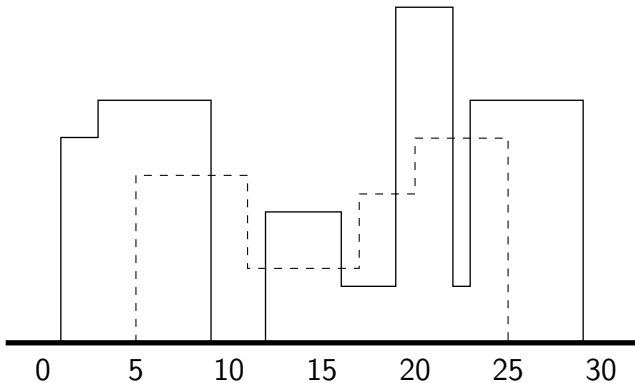
🌐 Add $(5, 9, 26)$ to $(1, 11, 3, 13, 9, 0, 12, 7, 16, 3, 19, 18, 22, 3, 23, 13, 29)$.



Source: adapted from [Manber 1989, Figure 5.6].

🌐 The skyline becomes $(1, 11, 3, 13, 9, 9, 19, 18, 22, 9, 23, 13, 29)$.

Merging Two Skylines



Source: adapted from [Manber 1989, Figure 5.7].

Balance Factors in Binary Trees

Problem

Given a binary tree T with n nodes, compute the balance factors of all nodes.

The **balance factor** of a node is defined as the **difference** between the height of the node's left subtree and the height of the node's right subtree.

Balance Factors in Binary Trees

Problem

Given a binary tree T with n nodes, compute the balance factors of all nodes.

The **balance factor** of a node is defined as the **difference** between the height of the node's left subtree and the height of the node's right subtree.

Motivation: an example of why we must **strengthen the hypothesis** (and hence the problem to be solved).

Balance Factors in Binary Trees (cont.)

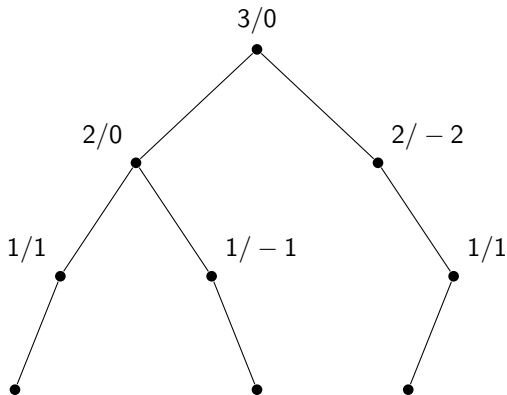


Figure: A binary tree. The numbers represent h/b , where h is the height and b is the balance factor.

Source: redrawn from [Manber 1989, Figure 5.8].

Induction hypothesis

We know how to compute balance factors of all nodes in trees that have $< n$ nodes.

Balance Factors in Binary Trees (cont.)

Induction hypothesis

We know how to compute balance factors of all nodes in trees that have $< n$ nodes.

Stronger induction hypothesis

We know how to compute balance factors **and heights** of all nodes in trees that have $< n$ nodes.

Maximum Consecutive Subsequence

Problem

Given a sequence x_1, x_2, \dots, x_n of real numbers (not necessarily positive), find a subsequence x_i, x_{i+1}, \dots, x_j (of consecutive elements) such that the sum of the numbers in it is maximum over all subsequences of consecutive elements.

Example:

In the sequence $(2, -3, 1.5, -1, 3, -2, -3, 3)$, the maximum subsequence is $(1.5, -1, 3)$.

Maximum Consecutive Subsequence

Problem

Given a sequence x_1, x_2, \dots, x_n of real numbers (not necessarily positive), find a subsequence x_i, x_{i+1}, \dots, x_j (of consecutive elements) such that the sum of the numbers in it is maximum over all subsequences of consecutive elements.

Example:

In the sequence $(2, -3, 1.5, -1, 3, -2, -3, 3)$, the maximum subsequence is $(1.5, -1, 3)$.

Motivation: another example of strengthening the hypothesis.

Induction hypothesis

We know how to find the maximum subsequence in sequences of size $< n$.

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Stronger induction hypothesis

We know how to find, in sequences of size $< n$, the maximum subsequence overall and the maximum subsequence that is a suffix.



Induction hypothesis

We know how to find the maximum subsequence in sequences of size $< n$.

Stronger induction hypothesis

We know how to find, in sequences of size $< n$, the maximum subsequence overall **and the maximum subsequence that is a suffix**.

Reasoning: the maximum subsequence of problem size n is obtained either

-  directly from the maximum subsequence of problem size $n - 1$ or
-  from appending the n -th element to the maximum suffix of problem size $n - 1$.

Maximum Consecutive Subsequence (cont.)

```
Algorithm Max_Consec_Subseq ( $X, n$ );  
begin  
     $Global\_Max := 0$ ;  
     $Suffix\_Max := 0$ ;  
    for  $i := 1$  to  $n$  do  
        if  $x[i] + Suffix\_Max > Global\_Max$  then  
             $Suffix\_Max := Suffix\_Max + x[i]$ ;  
             $Global\_Max := Suffix\_Max$   
        else if  $x[i] + Suffix\_Max > 0$  then  
             $Suffix\_Max := Suffix\_Max + x[i]$   
        else  $Suffix\_Max := 0$   
    end
```

The Knapsack Problem

Problem

Given an integer K and n items of different sizes such that the i -th item has an integer size k_i , find a subset of the items whose sizes sum to exactly K , or determine that no such subset exists.

The Knapsack Problem

Problem

Given an integer K and n items of different sizes such that the i -th item has an integer size k_i , find a subset of the items whose sizes sum to exactly K , or determine that no such subset exists.

Design Idea: use **strong induction** so that solutions to **all smaller instances** may be used.

The Knapsack Problem (cont.)

- Let $P(n, K)$ denote the problem where n is the number of items and K is the size of the knapsack.
- Induction hypothesis**
We know how to solve $P(n - 1, K)$.

The Knapsack Problem (cont.)

- Let $P(n, K)$ denote the problem where n is the number of items and K is the size of the knapsack.
- Induction hypothesis**
We know how to solve $P(n - 1, K)$.
- Stronger induction hypothesis**
We know how to solve $P(n - 1, k)$, for all $0 \leq k \leq K$.

The Knapsack Problem (cont.)

🌐 Let $P(n, K)$ denote the problem where n is the number of items and K is the size of the knapsack.

🌐 Induction hypothesis

We know how to solve $P(n - 1, K)$.

🌐 Stronger induction hypothesis

We know how to solve $P(n - 1, k)$, for all $0 \leq k \leq K$.

Reasoning: $P(n, K)$ has a solution if either

- ☀️ $P(n - 1, K)$ has a solution or
- ☀️ $P(n - 1, K - k_n)$ does, provided $K - k_n \geq 0$.

The Knapsack Problem (cont.)

An example of the table constructed for the knapsack problem:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$k_1 = 2$	O	-	I	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$k_2 = 3$	O	-	O	I	-	I	-	-	-	-	-	-	-	-	-	-	-
$k_3 = 5$	O	-	O	O	-	O	-	I	I	-	I	-	-	-	-	-	-
$k_4 = 6$	O	-	O	O	-	O	I	O	O	I	O	I	-	I	I	-	I

“I”: a solution containing this item has been found.

“O”: a solution without this item has been found.

“-”: no solution has yet been found.

Source: adapted from [Manber 1989, Figure 5.11].

The Knapsack Problem (cont.)

Algorithm Knapsack (S, K);

$P[0, 0].exist := true$;

for $k := 1$ **to** K **do**

$P[0, k].exist := false$;

for $i := 1$ **to** n **do**

for $k := 0$ **to** K **do**

$P[i, k].exist := false$;

if $P[i - 1, k].exist$ **then**

$P[i, k].exist := true$;

$P[i, k].belong := false$

else if $k - S[i] \geq 0$ **then**

if $P[i - 1, k - S[i]].exist$ **then**

$P[i, k].exist := true$;

$P[i, k].belong := true$