Algorithms 2017: Design by Induction

(Based on [Manber 1989])

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1 Introduction

Introduction

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

2 Evaluating Polynomials

Evaluating Polynomials

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

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

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

Evaluating Polynomials (cont.)

- Let $P_{n-1}(x) = a_{n-1}x^{n-1} + \cdots + a_1 x + a_0$.
- **Induction hypothesis** (first attempt)

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

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

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,

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

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*.

3 Maximal Induced Subgraph

Maximal Induced Subgraph

Problem 2. *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.*

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.

4 One-to-One Mapping

One-to-One Mapping

Problem 3. *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).*

Design Idea: similar to the previous problem; in the inductive step, we try to remove one element (that cannot possibly be part of the solution) to get a smaller instance.

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

5 Celebrity

Celebrity

Problem 4. *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.

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

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

6 The Skyline Problem

The Skyline Problem

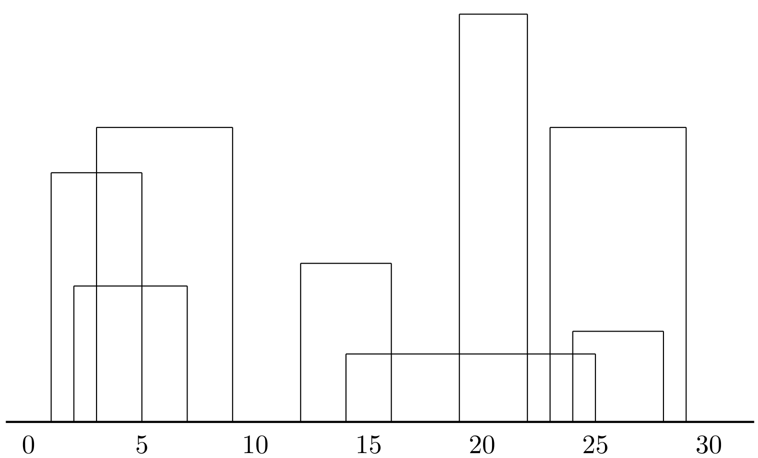
Problem 5. *Given the exact locations and shapes of several rectangular buildings in a city, draw the skyline (in two dimension) of these buildings, eliminating hidden lines.*

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

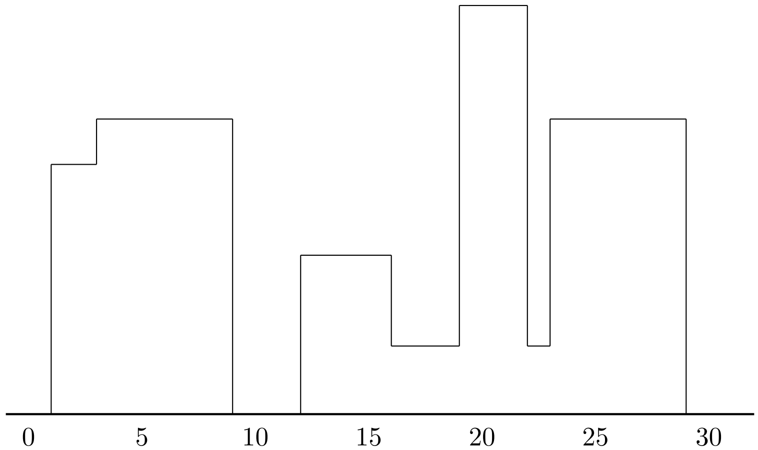
Representation of a Skyline

(1,**11**,5), (2,**6**,7), (3,**13**,9), (12,**7**,16), (14,**3**,25), (19,**18**,22), (23,**13**,29), and (24,**4**,28).



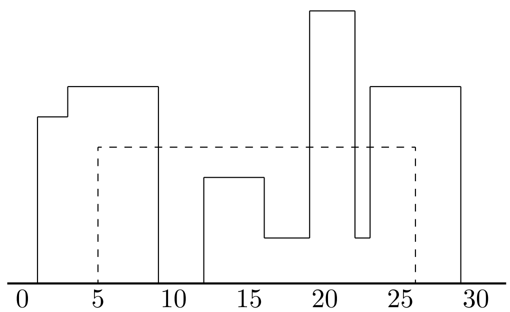
Representation of a Skyline (cont.)

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



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).



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

Merging Two Skylines

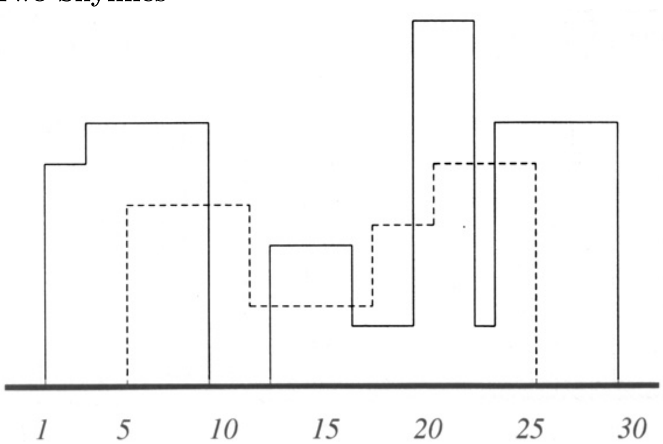


Figure 5.7 Merging two skylines.

Source: [Manber 1989].

7 Balance Factors in Binary Trees

Balance Factors in Binary Trees

Problem 6. *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.)

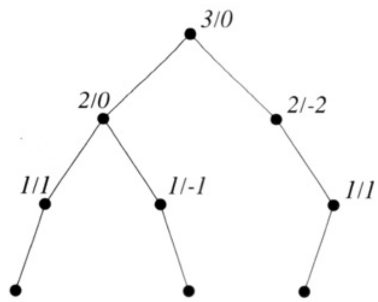


Figure 5.8 A binary tree. The numbers represent h/b, where h is the height and b is the balance factor.

Source: [Manber 1989].

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.

8 Maximum Consecutive Subsequence

Maximum Consecutive Subsequence

Problem 7. *Given a sequence $x_1, x_2, \cdots, x_n$ of real numbers (not necessarily positive) find a subsequence $x_i, x_{i+1}, \cdots, x_j$ (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.

Maximum Consecutive Subsequence (cont.)

- **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.

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

9 The Knapsack Problem

The Knapsack Problem

Problem 8. *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 $P(n-1, K)$.

- **Stronger induction hypothesis**

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

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.

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