

# Chapter 8

## Dynamic Programming

CS 473: Fundamental Algorithms, Fall 2011

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### 8.1 Longest Increasing Subsequence

#### 8.1.1 Longest Increasing Subsequence

##### 8.1.1.1 Sequences

**Definition 8.1.1** *Sequence*: an ordered list  $a_1, a_2, \dots, a_n$ . **Length** of a sequence is number of elements in the list.

**Definition 8.1.2**  $a_{i_1}, \dots, a_{i_k}$  is a **subsequence** of  $a_1, \dots, a_n$  if  $1 \leq i_1 < \dots < i_k \leq n$ .

**Definition 8.1.3** A sequence is **increasing** if  $a_1 < a_2 < \dots < a_n$ . It is **non-decreasing** if  $a_1 \leq a_2 \leq \dots \leq a_n$ . Similarly **decreasing** and **non-increasing**.

#### 8.1.2 Sequences

##### 8.1.2.1 Example...

**Example 8.1.4** (A) Sequence: 6, 3, 5, 2, 7, 8, 1

(B) Subsequence: 5, 2, 1

(C) Increasing sequence: 3, 5, 9

(D) Increasing subsequence: 2, 7, 8

##### 8.1.2.2 Longest Increasing Subsequence Problem

**Input** A sequence of numbers  $a_1, a_2, \dots, a_n$

**Goal** Find an *increasing subsequence*  $a_{i_1}, a_{i_2}, \dots, a_{i_k}$  of maximum length

**Example 8.1.5** (A) Sequence: 6, 3, 5, 2, 7, 8, 1

- (B) Increasing subsequences: 6, 7, 8 and 3, 5, 7, 8 and 2, 7 etc  
 (C) Longest increasing subsequence: 3, 5, 7, 8

### 8.1.2.3 Naïve Enumeration

Assume  $a_1, a_2, \dots, a_n$  is contained in an array  $A$

```

algLISNaive( $A[1..n]$ ):
   $max = 0$ 
  for each subsequence  $B$  of  $A$  do
    if  $B$  is increasing and  $|B| > max$  then
       $max = |B|$ 

  Output  $max$ 
  
```

Running time:  $O(n2^n)$ .

$2^n$  subsequences of a sequence of length  $n$  and  $O(n)$  time to check if a given sequence is increasing.

## 8.1.3 Recursive Approach: Take 1

### 8.1.3.1 LIS: Longest increasing subsequence

Can we find a recursive algorithm for LIS?

LIS( $A[1..n]$ ):

(A) Case 1: does not contain  $a_n$  in which case LIS( $A[1..n]$ ) = LIS( $A[1..(n-1)]$ )

(B) Case 2: contains  $a_n$  in which case LIS( $A[1..n]$ ) is not so clear.

**Observation:** if  $a_n$  is in the longest increasing subsequence then all the elements before it must be smaller.

### 8.1.3.2 Recursive Approach: Take 1

```

algLIS( $A[1..n]$ ):
  if ( $n = 0$ ) then return 0
   $m = \mathbf{algLIS}(A[1..(n-1)])$ 
   $B$  is subsequence of  $A[1..(n-1)]$  with
    only elements less than  $a_n$ 
  (* let  $h$  be size of  $B$ ,  $h \leq n-1$  *)
   $m = \max(m, 1 + \mathbf{algLIS}(B[1..h]))$ 
  Output  $m$ 
  
```

Recursion for running time:  $T(n) \leq 2T(n-1) + O(n)$ .

Easy to see that  $T(n)$  is  $O(n2^n)$ .

### 8.1.3.3 Recursive Approach: Take 2

LIS( $A[1..n]$ ):

(A) Case 1: does not contain  $a_n$  in which case LIS( $A[1..n]$ ) = LIS( $A[1..(n-1)]$ )

(B) Case 2: contains  $a_n$  in which case  $\text{LIS}(A[1..n])$  is not so clear.

**Observation 8.1.6** For second case we want to find a subsequence in  $A[1..(n-1)]$  that is restricted to numbers less than  $a_n$ . This suggests that a more general problem is  $\text{LIS\_smaller}(A[1..n], x)$  which gives the longest increasing subsequence in  $A$  where each number in the sequence is less than  $x$ .

### 8.1.3.4 Recursive Approach: Take 2

$\text{LIS\_smaller}(A[1..n], x)$  : length of longest increasing subsequence in  $A[1..n]$  with all numbers in subsequence less than  $x$

```

LIS\_smaller( $A[1..n], x$ ):
  if ( $n = 0$ ) then return 0
   $m = \text{LIS\_smaller}(A[1..(n-1)], x)$ 
  if ( $A[n] < x$ ) then
     $m = \max(m, 1 + \text{LIS\_smaller}(A[1..(n-1)], A[n]))$ 
  Output  $m$ 

```

```

LIS( $A[1..n]$ ):
  return LIS\_smaller( $A[1..n], \infty$ )

```

Recursion for running time:  $T(n) \leq 2T(n-1) + O(1)$ .

**Question:** Is there any advantage?

### 8.1.3.5 Recursive Algorithm: Take 2

**Observation:** The number of *different* subproblems generated by  $\text{LIS\_smaller}(A[1..n], x)$  is  $O(n^2)$ . Memoization the recursive algorithm leads to an  $O(n^2)$  running time!

**Question:** What are the recursive subproblem generated by  $\text{LIS\_smaller}(A[1..n], x)$ ?

(A) For  $0 \leq i < n$   $\text{LIS\_smaller}(A[1..i], y)$  where  $y$  is either  $x$  or one of  $A[i+1], \dots, A[n]$ .

**Observation:** previous recursion also generates only  $O(n^2)$  subproblems. Slightly harder to see.

### 8.1.3.6 Recursive Algorithm: Take 3

$\text{LISEnding}(A[1..n])$ : length of longest increasing sub-sequence that *ends* in  $A[n]$ .

**Question:** can we obtain a recursive expression?

$$\text{LISEnding}(A[1..n]) = \max_{i: A[i] < A[n]} (1 + \text{LISEnding}(A[1..i]))$$

### 8.1.3.7 Recursive Algorithm: Take 3

```
LIS_ending(A[1..n]):  
  if (n = 0) return 0  
  m = 1  
  for i = 1 to n - 1 do  
    if (A[i] < A[n]) then  
      m = max(m, 1 + LIS_ending(A[1..i]))  
  
  return m
```

```
LIS(A[1..n]):  
  return  $\max_{i=1}^n$  LIS_ending(A[1...i])
```

**Question:** How many distinct subproblems generated by **LISEnding**(A[1..n])?  $n$ .

### 8.1.3.8 Iterative Algorithm via Memoization

Compute the values **LISEnding**(A[1..i]) iteratively in a bottom up fashion.

```
LIS_ending(A[1..n]):  
  Array L[1..n]  
  (* L[i] = value of LIS_ending(A[1..i]) *)  
  for i = 1 to n do  
    L[i] = 1  
    for j = 1 to i - 1 do  
      if (A[j] < A[i]) do  
        L[i] = max(L[i], 1 + L[j])  
  return L
```

```
LIS(A[1..n]):  
  L = LIS_ending(A[1..n])  
  return the maximum value in L
```

### 8.1.3.9 Iterative Algorithm via Memoization

Simplifying:

```
LIS(A[1..n]):  
  Array L[1..n]  
  (* L[i] stores the value LIS-Ending(A[1..i]) *)  
  m = 0  
  for i = 1 to n do  
    L[i] = 1  
    for j = 1 to i - 1 do  
      if (A[j] < A[i]) do  
        L[i] = max(L[i], 1 + L[j])  
    m = max(m, L[i])  
  return m
```

*Correctness:* Via induction following the recursion

*Running time:*  $O(n^2)$ , *Space:*  $\Theta(n)$

### 8.1.3.10 Example

**Example 8.1.7** (A) Sequence: 6, 3, 5, 2, 7, 8, 1

(B) Longest increasing subsequence: 3, 5, 7, 8

- (A)  $L[i]$  is value of longest increasing subsequence ending in  $A[i]$
- (B) Recursive algorithm computes  $L[i]$  from  $L[1]$  to  $L[i - 1]$
- (C) Iterative algorithm builds up the values from  $L[1]$  to  $L[n]$

### 8.1.3.11 Memoizing LIS\_smaller

```
LIS( $A[1..n]$ ):  
   $A[n + 1] = \infty$  (* add a sentinel at the end *)  
  Array  $L[(n + 1), (n + 1)]$  (* two-dimensional array*)  
    (*  $L[i, j]$  for  $j \geq i$  stores the value LIS_smaller( $A[1..i], A[j]$ ) *)  
  for  $j = 1$  to  $n + 1$  do  
     $L[0, j] = 0$   
  for  $i = 1$  to  $n + 1$  do  
    for  $j = i$  to  $n + 1$  do  
       $L[i, j] = L[i - 1, j]$   
      if ( $A[i] < A[j]$ ) then  
         $L[i, j] = \max(L[i, j], 1 + L[i - 1, i])$   
  
  return  $L[n, (n + 1)]$ 
```

*Correctness:* Via induction following the recursion (take 2)

*Running time:*  $O(n^2)$ , *Space:*  $\Theta(n^2)$

## 8.1.4 Longest increasing subsequence

### 8.1.4.1 Another way to get quadratic time algorithm

- (A)  $G = (\{s, 1, \dots, n\}, \{\})$ : directed graph.
  - (A)  $\forall i, j$ : If  $i < j$  and  $A[i] < A[j]$  then add the edge  $i \rightarrow j$  to  $G$ .
  - (B)  $\forall i$ : Add  $s \rightarrow i$ .
- (B) The graph  $G$  is a **DAG**. **LIS** corresponds to longest path in  $G$  starting at  $s$ .
- (C) We know how to compute this in  $O(|V(G)| + |E(G)|) = O(n^2)$ .  
Comment: One can compute **LIS** in  $O(n \log n)$  time with a bit more work.

### 8.1.4.2 Dynamic Programming

- (A) Find a “smart” recursion for the problem in which the number of distinct subproblems is small; polynomial in the original problem size.
- (B) Eliminate recursion and find an iterative algorithm to compute the problems bottom up by storing the intermediate values in an appropriate data structure; need to find the right way or order the subproblem evaluation.

- (C) Estimate the number of subproblems, the time to evaluate each subproblem and the space needed to store the value. Evaluate the total running time.
- (D) Optimize the resulting algorithm further

## 8.2 Weighted Interval Scheduling

### 8.2.1 Weighted Interval Scheduling

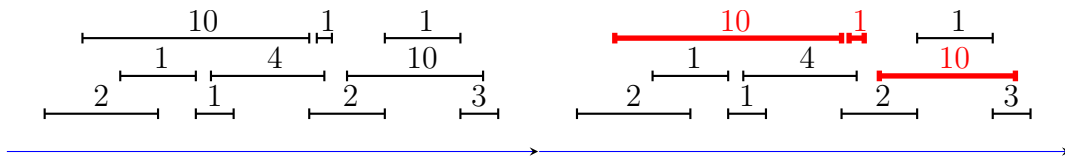
#### 8.2.2 The Problem

##### 8.2.2.1 Weighted Interval Scheduling

**Input** A set of jobs with start times, finish times and *weights* (or profits).

**Goal** Schedule jobs so that total weight of jobs is maximized.

- (A) Two jobs with overlapping intervals cannot both be scheduled!



### 8.2.3 Greedy Solution

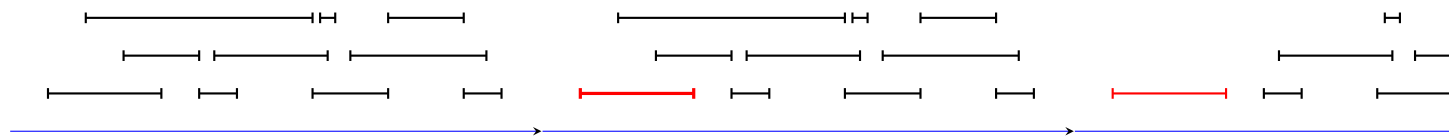
#### 8.2.4 Interval Scheduling

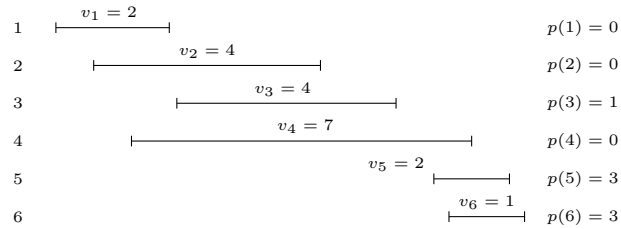
##### 8.2.4.1 Greedy Solution

**Input** A set of jobs with start and finish times to be scheduled on a resource; special case where all jobs have weight 1.

**Goal** Schedule as many jobs as possible.

- (A) Greedy strategy of considering jobs according to finish times produces optimal schedule (to be seen later).





**Example 8.2.2**

### 8.2.4.2 Greedy Strategies

- (A) Earliest finish time first
- (B) Largest weight/profit first
- (C) Largest weight to length ratio first
- (D) Shortest length first
- (E) ...

None of the above strategies lead to an optimum solution.

*Moral:* Greedy strategies often don't work!

## 8.2.5 Reduction to...

### 8.2.5.1 Max Weight Independent Set Problem

- (A) Given weighted interval scheduling instance  $I$  create an instance of max weight independent set on a graph  $G(I)$  as follows.
  - (A) For each interval  $i$  create a vertex  $v_i$  with weight  $w_i$ .
  - (B) Add an edge between  $v_i$  and  $v_j$  if  $i$  and  $j$  overlap.
- (B) *Claim:* max weight independent set in  $G(I)$  has weight equal to max weight set of intervals in  $I$  that do not overlap
- (C) **Independent Set** in general is NP-COMPLETE.
- (D) Can use structure of original problem for efficient algorithm?

We do not know an efficient (polynomial time) algorithm for independent set! Can we take advantage of the interval structure to find an efficient algorithm?

## 8.2.6 Recursive Solution

### 8.2.6.1 Conventions

**Definition 8.2.1** (A) Let the requests be sorted according to finish time, i.e.,  $i < j$  implies

$$f_i \leq f_j$$

(B) Define  $p(j)$  to be the largest  $i$  (less than  $j$ ) such that job  $i$  and job  $j$  are not in conflict

### 8.2.6.2 Towards a Recursive Solution

**Observation 8.2.3** Consider an optimal schedule  $\mathcal{O}$

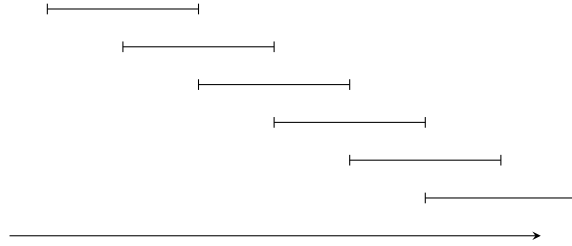


Figure 8.1: Bad instance for recursive algorithm

**Case  $n \in \mathcal{O}$  :** None of the jobs between  $n$  and  $p(n)$  can be scheduled. Moreover  $\mathcal{O}$  must contain an optimal schedule for the first  $p(n)$  jobs.

**Case  $n \notin \mathcal{O}$  :**  $\mathcal{O}$  is an optimal schedule for the first  $n - 1$  jobs.

### 8.2.6.3 A Recursive Algorithm

Let  $O_i$  be value of an optimal schedule for the first  $i$  jobs.

```

Schedule( $n$ ):
  if  $n = 0$  then return 0
  if  $n = 1$  then return  $w(v_1)$ 
   $O_{p(n)} \leftarrow$  Schedule( $p(n)$ )
   $O_{n-1} \leftarrow$  Schedule( $n - 1$ )
  if ( $O_{p(n)} + w(v_n) < O_{n-1}$ ) then
     $O_n = O_{n-1}$ 
  else
     $O_n = O_{p(n)} + w(v_n)$ 
  return  $O_n$ 

```

### Time Analysis

Running time is  $T(n) = T(p(n)) + T(n - 1) + O(1)$  which is ...

### 8.2.6.4 Bad Example

Running time on this instance is

$$T(n) = T(n - 1) + T(n - 2) + O(1) = \Theta(\phi^n)$$

where  $\phi \approx 1.618$  is the golden ratio.

(Because...  $T(n)$  is the  $n$  Fibonacci number.)

### 8.2.6.5 Analysis of the Problem

## 8.2.7 Dynamic Programming

### 8.2.7.1 Memo(r)ization

**Observation 8.2.4** (A) Number of different sub-problems in recursive algorithm is  $O(n)$ ; they are  $O_1, O_2, \dots, O_{n-1}$



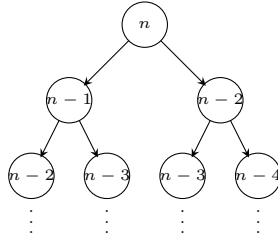


Figure 8.2: Label of node indicates size of sub-problem. Tree of sub-problems grows very quickly

(B) Exponential time is due to recomputation of solutions to sub-problems

### Solution

Store optimal solution to different sub-problems, and perform recursive call *only* if not already computed.

#### 8.2.7.2 Recursive Solution with Memoization

```

schdIMem(j)
  if j = 0 then return 0
  if M[j] is defined then (* sub-problem already solved *)
    return M[j]
  if M[j] is not defined then
    M[j] = max(w(vj) + schdIMem(p(j)), schdIMem(j - 1))
    return M[j]

```

### Time Analysis

- Each invocation,  $O(1)$  time plus: either return a computed value, or generate 2 recursive calls and fill one  $M[\cdot]$
- Initially no entry of  $M[]$  is filled; at the end all entries of  $M[]$  are filled
- So total time is  $O(n)$  (Assuming input is presorted...)

#### 8.2.7.3 Automatic Memoization

### Fact

Many functional languages (like LISP) automatically do memoization for recursive function calls!

## 8.2.7.4 Back to Weighted Interval Scheduling

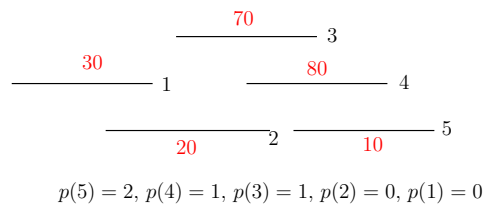
### Iterative Solution

```
M[0] = 0
for i = 1 to n do
    M[i] = max(w(v_i) + M[p(i)], M[i - 1])
```

$M$ : table of subproblems

- (A) Implicitly dynamic programming fills the values of  $M$ .
- (B) Recursion determines order in which table is filled up.
- (C) Think of decomposing problem first (recursion) and then worry about setting up table — this comes naturally from recursion.

### 8.2.7.5 Example



## 8.2.8 Computing Solutions

### 8.2.8.1 Computing Solutions + First Attempt

- (A) Memoization + Recursion/Iteration allows one to compute the optimal value. What

about the actual schedule?

```
M[0] = 0
S[0] is empty schedule
for i = 1 to n do
    M[i] = max(w(v_i) + M[p(i)], M[i - 1])
    if w(v_i) + M[p(i)] < M[i - 1] then
        S[i] = S[i - 1]
    else
        S[i] = S[p(i)] ∪ {i}
```

- (B) Naïvely updating  $S[]$  takes  $O(n)$  time
- (C) Total running time is  $O(n^2)$
- (D) Using pointers and linked lists running time can be improved to  $O(n)$ .

### 8.2.8.2 Computing Implicit Solutions

**Observation 8.2.5** *Solution can be obtained from  $M[]$  in  $O(n)$  time, without any additional information*

```

findSolution( j )
  if (j = 0) then return empty schedule
  if ( $v_j + M[p(j)] > M[j - 1]$ ) then
    return findSolution(p(j))  $\cup \{j\}$ 
  else
    return findSolution(j - 1)

```

Makes  $O(n)$  recursive calls, so **findSolution** runs in  $O(n)$  time.

### 8.2.8.3 Computing Implicit Solutions

A generic strategy for computing solutions in dynamic programming:

- (A) Keep track of the *decision* in computing the optimum value of a sub-problem. decision space depends on recursion
- (B) Once the optimum values are computed, go back and use the decision values to compute an optimum solution.

*Question:* What is the decision in computing  $M[i]$ ?

A: Whether to include  $i$  or not.

### 8.2.8.4 Computing Implicit Solutions

```

M[0] = 0
for i = 1 to n do
  M[i] = max( $v_i + M[p(i)]$ , M[i - 1])
  if ( $v_i + M[p(i)] > M[i - 1]$ ) then
    Decision[i] = 1 (* 1: i included in solution M[i] *)
  else
    Decision[i] = 0 (* 0: i not included in solution M[i] *)

S =  $\emptyset$ , i = n
while (i > 0) do
  if (Decision[i] = 1) then
    S = S  $\cup \{i\}$ 
    i = p(i)
  else
    i = i - 1
return S

```