VI. Dynamic Programming
Dynamic Programming – Overview

▶ Not a specific algorithm, but a technique (like Divide-and-Conquer and Greedy algorithms)
▶ Developed back in the day (1950s) when “programming” meant “tabular method” (like linear programming)
▶ Used for optimization problems
  ▶ Find a solution with the optimal value
  ▶ Minimization or maximization
Dynamic Programming

Four-step (two-phase) method:

1. Characterize the structure of an optimal solution
2. Recursively define the value of an optimal solution
3. Compute the value of an optimal solution in a bottom-up fashion
4. Construct an optimal solution from computed information
The rod cutting problem

Problem statement:

▶ Input:
   1) a rod of length \( n \)
   2) an array of prices \( p_i \) for a rod of length \( i \) for \( i = 1, \ldots, n \).

▶ Output:
   1) the maximum revenue \( r_n \) obtainable for rods whose length sum to \( n \)
   2) optimal cut, if necessary.

In short,

*How to cut a rod into pieces in order to maximize the revenue you can get?*
The rod cutting problem

Example

<table>
<thead>
<tr>
<th>rod length $i$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>price $p_i$</td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>17</td>
<td>17</td>
<td>20</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td>$r_i$</td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>13</td>
<td>17</td>
<td>18</td>
<td>22</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>$s_i$</td>
<td>1</td>
<td>2</td>
<td>3</td>
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<td>2</td>
<td>6</td>
<td>1</td>
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- $r_i$: maximum revenue of a rod of length $i$
- $s_i$: optimal size of the first piece to cut
The rod cutting problem

A brute-force solution:

*cut up a rod of length $n$ in $2^{n-1}$ different ways*

Cost: $\Theta(2^{n-1})$
The rod cutting problem

Dynamic Programming – Phase I:

Since every optimal solution $r_n$ has a leftmost cut with length $i$, the optimal revenue $r_n$ is given by

$$r_n = \max\{p_1 + r_{n-1}, p_2 + r_{n-2}, \ldots, p_{n-1} + r_1, p_n + r_0\}$$

$$= \max_{1 \leq i \leq n} \{p_i + r_{n-i}\}$$

$$= p_{i^*} + r_{n-i^*}$$

(2)

where

$$i^* = \text{the index attains the maximum}$$

$$= \text{the length of the leftmost cut}$$
The rod cutting problem

Dynamic Programming – Phase II:

- How to compute \( r_n \) by the expression (1)?

  1. Recursive solution:
     - top-down, no memoization
     - Cost:
       \[
       T(n) = 1 + \sum_{j=0}^{n-1} T(j) = \Theta(2^n)
       \]

  2. Iterative solution
     - bottom-up, memoization (Pseudocode – see next page)
     - Cost:
       \[
       T(n) = \Theta(n^2)
       \]
The rod cutting problem

cut-rod(p,n)
// an iterative (bottom-up) procedure for finding ‘‘r’’ and
// the optimal size of the first piece to cut off ‘‘s’’
Let r[0...n] and s[0...n] be new arrays
r[0] = 0
for j = 1 to n
    // find q = max{p[i]+r[j-i]} for 1 <= i <= j
    q = -infty
    for i = 1 to j
        if q < p[i] + r[j-i]
            q = p[i] + r[j-i]
            s[j] = i
        end if
    end for
    r[j] = q
end for
return r and s
## The rod cutting problem

### Example

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- $s_i$: optimal size of the first piece to cut

Note: $s_i = i_*$ in expression (2).