

11. Dynamic Programming Introduction

CPSC 535

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Dynamic Programming

- ▶ pattern for designing algorithms
- ▶ *programming*:
 - ▶ optimize subject to constraints
 - ▶ (same as Linear Programming)
 - ▶ **not** writing programs
- ▶ *dynamic*: curious buzzword
- ▶ specialized tool
 - ▶ dynamic programming only applies to problems with *overlapping subproblems*
 - ▶ rare
 - ▶ huge speedup over naïve algorithms for such problems

Big Ideas

- ▶ important algorithm design approach in its own right
- ▶ problem solving to view a problem in a different way
- ▶ **time-space trade-off**
 - ▶ speedup costs space
- ▶ **efficiency-complexity trade-off**
 - ▶ top-down, bottom-up variants
 - ▶ top-down is simpler to design and implement
 - ▶ bottom-up has faster constant factors

Optimization, Value, Solution

- ▶ dynamic programming usually applies to **optimization** problems
 - ▶ correct output “minimizes” or “maximizes” something
- ▶ **value**: quality of the solution
 - ▶ quantity to minimize/maximize
- ▶ designing a dynamic programming algorithm to...
 - ▶ ...calculate optimal **value** is simpler
 - ▶ ...calculate optimal **solution** is more complicated
- ▶ \therefore some examples and exercises only involves **values**
- ▶ algo's for **solutions** are more practical but difficult

Example: Vertex Cover

vertex cover problem

input: an undirected graph $G = (V, E)$

output: a vertex cover C of minimum size

- ▶ solution = a set of vertices C
- ▶ value = size of C
- ▶ optimal = minimize $|C|$

vertex cover value problem

input: an undirected graph $G = (V, E)$

output: the minimum size of a vertex cover of G

- ▶ note: output data type is an integer, not a set

Example: Bipartite Matching

bipartite maximum matching problem

input: an undirected bipartite graph $G = (V, E)$ with parts $V = L \cup R$

output: a matching $M \subseteq E$ where the number of matched vertices is maximum

- ▶ solution = a set of edges M
- ▶ value = size of M

bipartite maximum matching value problem

input: an undirected bipartite graph $G = (V, E)$ with parts $V = L \cup R$

output: the maximum number of edges in a matching of G

- ▶ note: output data type is an integer, not a set

Ties

- ▶ we say **an** optimal solution
- ▶ not **the** optimal solution
- ▶ multiple solutions may have same value
- ▶ any of these are correct
- ▶ examples:
 - ▶ vertex cover: “a vertex cover C of minimum size”
 - ▶ bipartite matching: “a matching $M \subseteq E$ where the number of matched vertices is maximum”
- ▶ not worrying about ties simplifies dynamic programming algorithms

The Main Idea

- ▶ dynamic programming works on a problem where...
 - ▶ a solution has a **recursive structure**
 - ▶ so we *could* design a naïve divide-and-conquer algorithm
 - ▶ **but**, subproblems **overlap**
 - ▶ so divide-and-conquer would do the same work repeatedly
 - ▶ would be slow (often exponential time)
- ▶ idea: store subproblem solutions in a **table** (array or hash dictionary)
- ▶ only solve subproblems not already in table
- ▶ \therefore each subproblem is solved **only once**
- ▶ fast polynomial time, often $\Theta(n)$ or $\Theta(n^2)$

Top-Down versus Bottom Up

- ▶ two ways to write the pseudocode
- ▶ **top-down**
 - ▶ improvement to divide-and-conquer pseudocode
 - ▶ add a base case that checks for a solution in the table
 - ▶ simple to derive from divide-and-conquer algorithm
 - ▶ usually depends on a hash dictionary data structure, so expected time
- ▶ **bottom-up**
 - ▶ clean-sheet redesign
 - ▶ nested loops explicitly solve problems in sorted order
 - ▶ base case, larger subproblems, ..., full problem
 - ▶ store subproblems in array (not hash table)
 - ▶ no recursion or hash table \Rightarrow faster constant factors

Design Process

1. Identify the problem's **solution** and **value**, and note which is our **goal**.
2. Derive a **recurrence** for an optimal value.
3. Design a divide-and-conquer algorithm that computes an **optimal value**.
4. Design a dynamic programming algorithm that computes an **optimal value**.
 - 4.1 **top-down** alternative: add table base case (**memoization**)
 - 4.2 **bottom-up** alternative: rewrite to use bottom-up loops instead of recursion
5. (if goal is a solution algo.) Design a dynamic programming algorithm that computes an **optimal solution**.

Rod Cutting Problem

story:

- ▶ have a rod of metal n inches long
- ▶ can chop it into pieces of size $1, 2, \dots, n$
- ▶ total length of all pieces = n
- ▶ market price of a i -inch piece is p_i
- ▶ market price of a 0-inch piece is 0
- ▶ goal: maximize total price of the pieces

rod cutting value problem

input: an array of non-negative prices $P = \langle p_1, \dots, p_n \rangle$

output: the maximum total price that can be achieved by cutting an n -inch rod into pieces

Example with $n = 4$

i	1	2	3	4
p_i	3	7	8	11

Ways of cutting $\square\square\square\square$:

1. $\square\square\square\square : p_4 = \11
2. $\square \mid \square\square\square : p_1 + p_3 = \$3 + \$8 = \11
3. $\square\square \mid \square\square : p_2 + p_2 = \$7 + \$7 = \14
4. $\square\square\square \mid \square : p_3 + p_1 = \$8 + \$3 = \11
5. $\square \mid \square \mid \square\square : p_1 + p_1 + p_2 = \$3 + \$3 + \$7 = \$13$
6. $\square \mid \square\square \mid \square : p_1 + p_2 + p_1 = \$3 + \$7 + \$3 = \$13$
7. $\square\square \mid \square \mid \square : p_2 + p_1 + p_1 = \$7 + \$3 + \$3 = \$13$
8. $\square \mid \square \mid \square \mid \square : p_1 + p_1 + p_1 + p_1 = \$3 + \$3 + \$3 + \$3 = \12

Greedy Fails

- ▶ greedy heuristics are **not correct** for this problem
- ▶ note that there is no requirement that prices p_i obey “common sense” market dynamics
- ▶ e.g. it is allowed for $p_4 > p_5$
- ▶ example of an **incorrect** greedy heuristic: find length i with highest unit price p_i/i , then make $\lceil n/i \rceil$ pieces of length i
- ▶ fails when the leftover $n - \lceil n/i \rceil$ inches could be used better
- ▶ Recall: the designer of a greedy algorithm has the burden of **proving** their heuristic is correct
- ▶ **Tip:** if you are told to design a dynamic programming algorithm, don't waste time with greedy algorithms

Rod Cutting Step 1

1. Identify the problem's **solution** and **value**, and note which is our **goal**.

rod cutting value problem

input: an array of non-negative prices $P = \langle p_1, \dots, p_n \rangle$

output: the maximum total price that can be achieved by cutting an n -inch rod into pieces

- ▶ **solution:** list of piece lengths e.g. $\langle 2, 2 \rangle$
- ▶ **value:** total price e.g. \$14
- ▶ **goal:** **value**

Rod Cutting Step 2

2. Derive a **recurrence** for an optimal value.

- ▶ define r_i = the maximum total price starting from i inches
- ▶ base case: $r_0 = 0$
- ▶ general case:
 - ▶ let $j \equiv$ current rod length i.e. current value of n
 - ▶ **think** divide-and-conquer; define r_j in terms of $r_{<j}$
 - ▶ make the problem **one piece** smaller
 - ▶ try to make one cut, then recursively use the remaining inches
 - ▶ try every option and keep the optimal one

$$r_j = \max_{1 \leq i \leq j} (p_i + r_{j-i})$$

Rod Cutting Step 3

3. Design a divide-and-conquer algorithm that computes an **optimal value**.

```
1: function CUT-ROD-DC(P, n)
2:   if n == 0 then
3:     return 0
4:   end if
5:    $q = -\infty$ 
6:   for  $i$  from 1 to  $n$  do
7:      $q = \max(q, P[i] + \text{CUT-ROD-DC}(P, n-i))$ 
8:   end for
9:   return  $q$ 
10: end function
```


Sidebar: Analysis of CUT-ROD-DC

- ▶ CUT-ROD-DC corresponds directly to the r_i definition
- ▶ **but** it is very slow
- ▶ fundamental problem: CUT-ROD-DC calls itself many times
 - ▶ each iteration of the **for** loop is a recursive call
 - ▶ each of those has a **for** loop with recursive calls. . .
- ▶ recall: fast divide-and-conquer algorithms usually call themselves 1–2 times
- ▶ *Claim:* The time complexity of CUT-ROD-DC is $O(2^{n-1})$.
- ▶ dynamic programming will circumvent all this recursion

Rod Cutting Step 4.a

4. Design a dynamic programming algorithm that computes an **optimal value**.

4.1 **top-down** alternative: add table base case (**memoization**)

- ▶ **memoization**: use a hash dictionary to make a “memo” of pre-calculated solutions
- ▶ use i as key in table T (same API as hash tables in deck 4)
- ▶ after we compute an r_i , set $r_i.key = i$ and insert r_i into T
- ▶ if T does not contain key i , then we haven't computed r_i yet
- ▶ need two functions
 - ▶ public non-recursive function to create T and start recursion
 - ▶ private recursive function that expects T to exist

Rod Cutting Step 4.a

```
1: function CUT-ROD-MEMOIZED( $P, n$ )
2:   HASH-TABLE-CREATE( $T$ )
3:   return CUT-ROD-MEMO-REC( $T, P, n$ )
4: end function
5: function CUT-ROD-MEMO-REC( $T, P, n$ )
6:    $q$  = HASH-TABLE-SEARCH( $T, n$ )
7:   if  $q \neq \text{NIL}$  then
8:     return  $q$ 
9:   end if
10:  if  $n == 0$  then
11:     $q = 0$ 
12:  else
13:     $q = -\infty$ 
14:    for  $i$  from 1 to  $n$  do
15:       $q = \max(q, P[i] + \text{CUT-ROD-MEMO-REC}(T, P, n - i))$ 
16:    end for
17:  end if
18:   $q.\text{key} = n$ 
19:  HASH-TABLE-INSERT( $q$ )
20:  return  $q$ 
21: end function
```

Rod Cutting Step 4.b

4. Design a dynamic programming algorithm that computes an **optimal value**.
 - 4.1 **top-down** alternative: add table base case (**memoization**)
 - 4.2 **bottom-up** alternative: rewrite to use bottom-up loops instead of recursion
- ▶ observe: in CUT-ROD-MEMOIZED, keys are inserted into T in order $0, 1, \dots, n$
- ▶ **bottom-up**: write an explicit **for** loop that computes and stores every general case r_i in order r_1, \dots, r_n
- ▶ base case is computed and stored before the loop
- ▶ convenient to use an array instead of hash table
- ▶ define $R[i] = r_i$
- ▶ no more recursion, just loops

Rod Cutting Step 4.b

```
1: function CUT-ROD-BU( $P[1..n]$ )
2:   Create array  $R[0..n]$ 
3:    $R[0] = 0$ 
4:   for  $j$  from 1 to  $n$  do
5:      $q = -\infty$ 
6:     for  $i$  from 1 to  $j$  do
7:        $q = \max(q, P[i] + R[j - i])$ 
8:     end for
9:      $R[j] = q$ 
10:  end for
11:  return  $R[n]$ 
12: end function
```

Bottom-Up Analysis

- ▶ CUT-ROD-BU is clearly $\Theta(n^2)$ time
- ▶ (Note: easy analysis)

Top-Down Analysis

- ▶ trickier analysis
- ▶ observe: hash **if** statement guarantees that each subproblem is solved exactly once
- ▶ solving subproblem i , not counting recursion: $\Theta(i)$ time due to **for** loop
- ▶ total of all subproblems is $\sum_{i=1}^n i \in \Theta(n^2)$
- ▶ hash operations add “expected” qualifier
- ▶ \therefore CUT-ROD-MEMOIZED takes $\Theta(n^2)$ expected time
- ▶ with effort we could replace the hash table with an array for $\Theta(n^2)$ worst-case time
- ▶ CUT-ROD-MEMOIZED has worse constant factors due to the overhead of recursive function calls

Trade-Offs

Factor	Naïve	TDDP	BUDP
Ease of design	easiest	difficult	very difficult
Ease of analysis	medium	difficult	easy
Time efficiency	$O(2^{n-1})$	$\Theta(n^2)$ exp.	$\Theta(n^2)$ w/ fast const.
Space overhead	n/a	$O(n)$ hashtable	$O(n)$ array

- ▶ according to principles, **bottom up dynamic programming** is superior
- ▶ but top-down dynamic programming is a close second

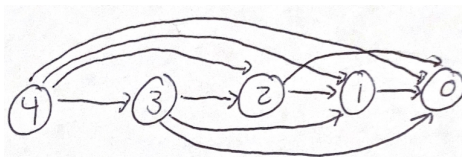
Subproblem Graphs

- ▶ solutions have a recursive structure

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

- ▶ a general-case solution depends on other solution(s)
- ▶ algorithm must compute solutions in an order that satisfies dependencies
- ▶ memoization automates this, with overhead
- ▶ bottom-up loops must be designed carefully to iterate in satisfactory order
- ▶ visualize dependencies in a **subproblem graph**

Subproblem Graphs



- ▶ vertex i = subproblem i
- ▶ directed edge (i, j) = computing i requires solution to j
- ▶ subproblem i must wait until all outgoing neighbors have been computed
- ▶ top-down manages with hashtable
- ▶ bottom up manages with loop iteration order

Rod Cutting Step 5

5. (if goal is a solution algo.) Design a dynamic programming algorithm that computes an **optimal solution**.

rod cutting value problem

input: an array of non-negative prices $P = \langle p_1, \dots, p_n \rangle$

output: the maximum total price that can be achieved by cutting an n -inch rod into pieces

rod cutting problem

input: an array of non-negative prices $P = \langle p_1, \dots, p_n \rangle$

output: the list of cut-lengths of maximum total price for an n -inch rod

Storing All Subproblem Solutions Is Expensive

- ▶ solution to rod cutting problem: a list of cut-lengths; $O(n)$ space each
- ▶ our algorithms compute $n + 1$ solutions
- ▶ storing all subproblem solutions would takes $O((n + 1) \times n) = O(n^2)$ space, **expensive**
- ▶ instead, store only $O(n)$ information

Backtracking

- ▶ algorithm computes optimal value, and **logs (records) how it made each decision**
- ▶ after all optimal values have been computed, follow a “trail” to create solution object
- ▶ trail ends at the optimal solution
- ▶ each log entry says how to go one step backwards
- ▶ follow them until we get to the start (a base case)
- ▶ traverses solution in backwards order; reverse it if order matters
- ▶ backtracking is usually only $O(n)$ time, and $O(n)$ space overhead

Rod Cutting Step 5

5. (if goal is a solution algo.) Design a dynamic programming algorithm that computes an **optimal solution**.

- ▶ bottom-up algo. makes optimal choices with

$$q = \max(q, P[i] + R[j - i])$$

step

- ▶ i.e. it chooses how many inches to cut right now
- ▶ **log** these choices in another array
- ▶ recall $R[j]$ = maximum total price starting from j inches
- ▶ define $S[j]$ = size of the first optimal cut starting from j inches
- ▶ need to update pseudocode to
 - ▶ create S
 - ▶ update S inside the loops
 - ▶ at the end, backtrack S to compute a list of lengths

Rod Cutting Step 5 – Pseudocode

```
1: function CUT-ROD-SOLUTION( $P[1..n]$ )
2:   Create arrays  $R[0..n]$  and  $S[0..n]$ 
3:    $R[0] = 0$ 
4:   for  $j$  from 1 to  $n$  do
5:      $q = -\infty$ 
6:     for  $i$  from 1 to  $j$  do
7:       if  $q < (P[i] + R[j - i])$  then
8:          $q = P[i] + R[j - i]$ 
9:          $S[j] = i$ 
10:      end if
11:    end for
12:     $R[j] = q$ 
13:  end for
14:  soln = empty list
15:   $j = n$ 
16:  while  $j > 0$  do
17:    soln.add( $S[j]$ )
18:     $j = j - S[j]$ 
19:  end while
20:  reverse soln
21:  return soln
22: end function
```

Analysis

- ▶ CUT-ROD-SOLUTION solves the *rod cutting problem*
 - ▶ it returns a list of cut-lengths, not a price
- ▶ analysis is actually straightforward
- ▶ time efficiency:
 - ▶ nested **for** loops: $\Theta(n^2)$
 - ▶ backtracking: **while** loop iterates at most n times $\Rightarrow \Theta(n)$ time
 - ▶ reverse soln: $\Theta(n)$
 - ▶ total $\Theta(n^2 + n + n) = \Theta(n^2)$ time
- ▶ space efficiency: R and S take $\Theta(n + n) = \Theta(n)$ space
- ▶ (same as the step-4 algorithms)