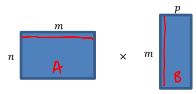
CS4102 Algorithms
Spring 2019

Warm up

How many arithmetic operations are required to multiply a $n \times m$ Matrix with a $m \times p$ Matrix?

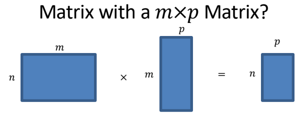
(don't overthink this)



m multiplies
m−1 additions
m-1
$\underline{a_{11} \cdot b_{11}} + \underline{a_{21} \cdot b_{12}} + \cdots$
m

1

How many arithmetic operations are required to multiply a $n \times m$ Matrix with a $m \times p$ Matrix?



- m multiplications and additions per element
- $n \cdot p$ elements to compute
- Total cost: $m \cdot n \cdot p$

$n \cdot p(m + m-1)$

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Today's Keywords

- Dynamic Programming
- Matrix Chaining
- Seam Carving
- Longest Common Subsequence

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CLRS Readings

- Chapter 15

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Administrativa

- HW5 out by tomorrow morning
  – Due March 27 at 11pm
  – Seam Carving!
  – Dynamic Programming (implementation)
  – Java or Python
- Midterm
  – Grading underway! Should be returned tomorrow
- HW4 grading in-progress

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Dynamic Programming

- Requires Optimal Substructure
  – Solution to larger problem contains the solutions to smaller ones
- Idea:
  1. Identify recursive structure of the problem
     - What is the "last thing" done?
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Generic Top-Down Dynamic Programming Soln

```
mem = {}
def myDPalgo(problem):
    if mem[problem] not blank:
        return mem[problem]
    if baseCase(problem):
        solution = solve(problem)
        mem[problem] = solution
        return solution
    for subproblem of problem:
        subsolutions.append(myDPalgo(subproblem))
    solution = OptimalSubstructure(subsolutions)
    mem[problem] = solution
    return solution
```

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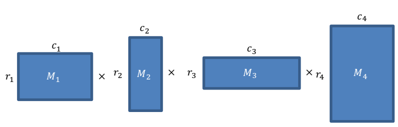
Matrix Chaining

- Given a sequence of Matrices $(M_1, \dots, M_n)$, what is the most efficient way to multiply them?



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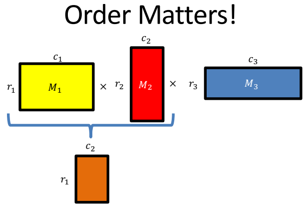
$c_1 = r_2$
$c_2 = r_3$

Order Matters!



- $(M_1 \times M_2) \times M_3$
  - uses $(c_1 \cdot r_1 \cdot c_2) + c_2 \cdot r_1 \cdot c_3$ operations

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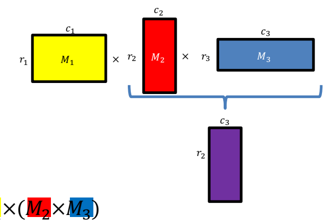
$c_1 = r_2$
$c_2 = r_3$

Order Matters!



- $M_1 \times (M_2 \times M_3)$
  - uses $c_1 \cdot r_1 \cdot c_3 + (c_2 \cdot r_2 \cdot c_3)$ operations

10

$c_1 = r_2$
$c_2 = r_3$

Order Matters!

- $(M_1 \times M_2) \times M_3$
  - uses $(c_1 \cdot r_1 \cdot c_2) + c_2 \cdot r_1 \cdot c_3$ operations
  - $(10 \cdot 7 \cdot 20) + 20 \cdot 7 \cdot 8 = 2520$
- $M_1 \times (M_2 \times M_3)$
  - uses $c_1 \cdot r_1 \cdot c_3 + (c_2 \cdot r_2 \cdot c_3)$ operations
  - $10 \cdot 7 \cdot 8 + (20 \cdot 10 \cdot 8) = 2160$

$M_1 = 7 \times 10$
$M_2 = 10 \times 20$
$M_3 = 20 \times 8$
$c_1 = 10$
$c_2 = 20$
$c_3 = 8$
$r_1 = 7$
$r_2 = 10$
$r_3 = 20$

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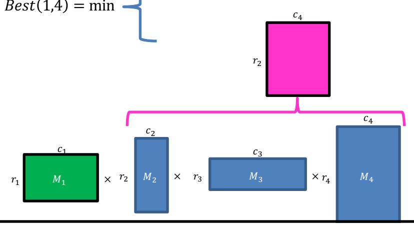
1. Identify the Recursive Structure of the Problem

$Best(1,n)$ = cheapest way to multiply together M_1 through M_n

$$Best(1,4) = \min \begin{cases} Best(2,4) + r_1 r_2 c_4 \end{cases}$$



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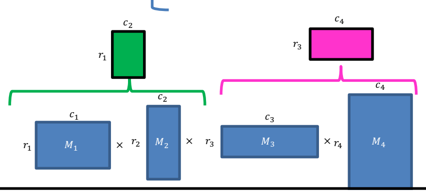

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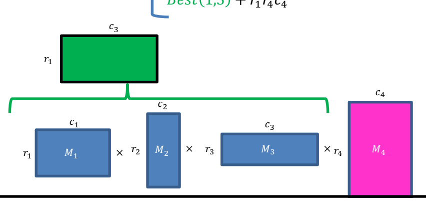
$$Best(1,4) = \min \begin{cases} Best(2,4) + r_1 r_2 c_4 \\ Best(1,2) + Best(3,4) + r_1 r_3 c_4 \\ Best(1,3) + r_1 r_4 c_4 \end{cases}$$



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1. Identify the Recursive Structure of the Problem

- In general:

$Best(i,j) =$ cheapest way to multiply together M_i through M_j

$$Best(i,j) = \min_{k=i}^{j-1}\left(\overset{r_i \times c_k}{Best(i,k)} + \overset{r_{k+1} \times c_j}{Best(k+1,j)} + r_i r_{k+1} c_j\right) \qquad c_k = r_{k+1}$$

$Best(i,i) = 0$

$$Best(1,n) = \min \begin{cases} Best(2,n) + r_1 r_2 c_n \\ Best(1,2) + Best(3,n) + r_1 r_3 c_n \\ Best(1,3) + Best(4,n) + r_1 r_4 c_n \\ Best(1,4) + Best(5,n) + r_1 r_5 c_n \\ \ldots \\ Best(1,n-1) + r_1 r_n c_n \end{cases}$$

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Dynamic Programming

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1. Identify the Recursive Structure of the Problem

- In general:

$Best(i,j) =$ cheapest way to multiply together M_i through M_j

$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right) \qquad O(4^n)$$

Read from M[n] if present

$Best(i,i) = 0$

Save to M[n]

$$Best(1,n) = \min \begin{cases} Best(2,n) + r_1 r_2 c_n \\ Best(1,2) + Best(3,n) + r_1 r_3 c_n \\ Best(1,3) + Best(4,n) + r_1 r_4 c_n \\ Best(1,4) + Best(5,n) + r_1 r_5 c_n \\ \ldots \\ Best(1,n-1) + r_1 r_n c_n \end{cases}$$

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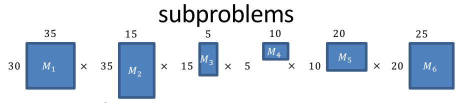
2. Select a good order for solving subproblems



$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$$

$$Best(i,i) = 0$$

$j =$	1	2	3	4	5	6
$i =$ 1	0					
2		0				
3			0			
4				0		
5					0	
6						0

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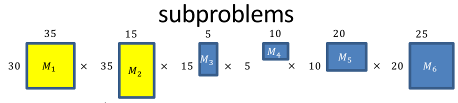
2. Select a good order for solving subproblems



$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$$

$$Best(i,i) = 0$$

$j =$	1	2	3	4	5	6
$i =$ 1	0	15750				
2		0				
3			0			
4				0		
5					0	
6						0

$$Best(1,2) = \min \begin{cases} Best(1,1) + Best(2,2) + r_1 r_2 c_2 \end{cases}$$

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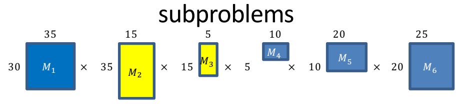
2. Select a good order for solving subproblems



$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$$

$$Best(i,i) = 0$$

$j =$ 1	2	3	4	5	6	$i =$
0	15750					1
	0	2625				2
		0				3
			0			4
				0		5
					0	6

$$Best(2,3) = \min\left\{ Best(2,2) + Best(3,3) + r_2 r_3 c_3 \right.$$

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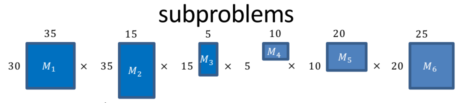
2. Select a good order for solving subproblems



$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$$

$$Best(i,i) = 0$$

$j =$ 1	2	3	4	5	6	$i =$
0	15750					1
	0	2625				2
		0	750			3
			0	1000		4
				0	5000	5
					0	6

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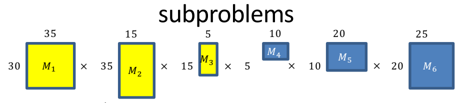
2. Select a good order for solving subproblems



$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$$

$$Best(i,i) = 0$$

$j =$ 1	2	3	4	5	6	$i =$
0	15750	7875				1
	0	2625				2
		0	750			3
			0	1000		4
				0	5000	5
					0	6

$$r_1 r_2 c_3 = 30 \cdot 35 \cdot 5 = 5250$$
$$r_1 r_3 c_3 = 30 \cdot 15 \cdot 5 = 2250$$

$$Best(1,3) = \min\left\{\begin{array}{l} \overset{0}{Best(1,1)} + \overset{2625}{Best(2,3)} + r_1 r_2 c_3 \\ \underset{15750}{Best(1,2)} + \underset{0}{Best(3,3)} + r_1 r_3 c_3 \end{array}\right.$$

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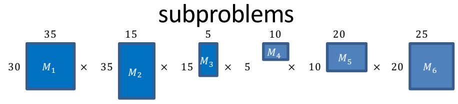
2. Select a good order for solving subproblems



$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$$

$$Best(i,i) = 0$$

$j =$ 1	2	3	4	5	6	i
0	15750	7875				1
	0	2625				2
		0	750			3
			0	1000		4
				0	5000	5
					0	6

To find $Best(i,j)$: Need all preceding terms of row i and column j

Conclusion: solve in order of diagonal

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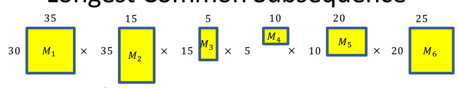
Longest Common Subsequence



$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$$

$$Best(i,i) = 0$$

$j =$ 1	2	3	4	5	6	i
0	15750	7875	9375	11875	15125	1
	0	2625	4375	7125	10500	2
		0	750	2500	5375	3
			0	1000	3500	4
				0	5000	5
					0	6

$$Best(1,6) = \min \begin{cases} Best(1,1) + Best(2,6) + r_1 r_2 c_6 \\ Best(1,2) + Best(3,6) + r_1 r_3 c_6 \\ Best(1,3) + Best(4,6) + r_1 r_4 c_6 \\ Best(1,4) + Best(5,6) + r_1 r_5 c_6 \\ Best(1,5) + Best(6,6) + r_1 r_6 c_6 \end{cases}$$

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Run Time

1. Initialize $Best[i,i]$ to be all 0s
2. Starting at the main diagonal, working to the upper-right, fill in each cell using: $\Theta(n^2)$ cells in the Array
   1. $Best[i,i] = 0$
   2. $Best[i,j] = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$

      $\Theta(n)$ options for each cell

$\Theta(n^3)$ overall run time

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Backtrack to find the best order

"remember" which choice of k was the minimum at each cell

$$Best(i,j) = \min_{k=i}^{j-1}\left(Best(i,k) + Best(k+1,j) + r_i r_{k+1} c_j\right)$$

$$Best(i,i) = 0$$

$j =$	1	2	3	4	5	6	$= i$
	0	15750	7875 1	9375	11875	15125 3	1
		0	2625	4375	7125	10500	2
			0	750	2500	5375	3
				0	1000	3500 5	4
					0	5000	5
						0	6

$$Best(1,6) = \min \begin{cases} Best(1,1) + Best(2,6) + r_1 r_2 c_6 \\ Best(1,2) + Best(3,6) + r_1 r_3 c_6 \\ \boxed{Best(1,3) + Best(4,6) + r_1 r_4 c_6} \\ Best(1,4) + Best(5,6) + r_1 r_5 c_6 \\ Best(1,5) + Best(6,6) + r_1 r_6 c_6 \end{cases}$$

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Movie Time!

In Season 9 Episode 7 "The Slicer" of the hit 90s TV show *Seinfeld*, George discovers that, years prior, he had a heated argument with his new boss, Mr. Kruger. This argument ended in George throwing Mr. Kruger's boombox into the ocean. How did George make this discovery?

https://www.youtube.com/watch?v=pSB3HdmLcY4

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Seam Carving

- Method for image resizing that doesn't scale/crop the image

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Seam Carving

- Method for image resizing that doesn't scale/crop the image

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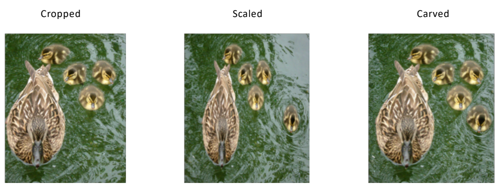
Seam Carving

- Method for image resizing that doesn't scale/crop the image



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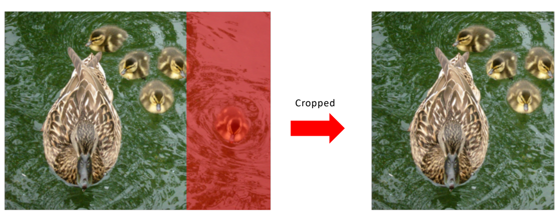
Cropping

- Removes a "block" of pixels



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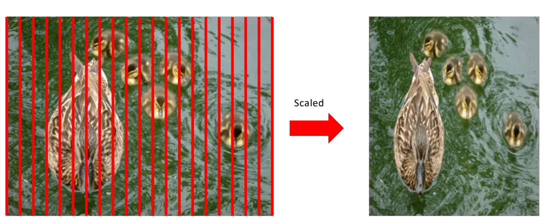
Scaling

- Removes "stripes" of pixels



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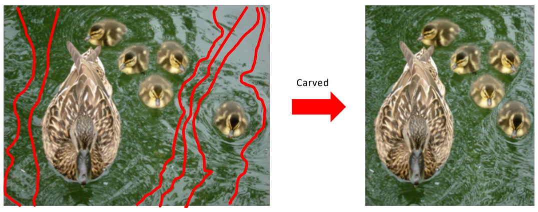
Seam Carving

- Removes "least energy seam" of pixels
- http://rsizr.com/



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Seattle Skyline

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Energy of a Seam

- Sum of the energies of each pixel
  - $e(p)$ = energy of pixel p
- Many choices
  - E.g.: change of gradient (how much the color of this pixel differs from its neighbors)
  - Particular choice doesn't matter, we use it as a "black box"

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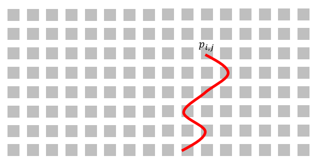
Identify Recursive Structure

Let $S(i, j)$ = least energy seam from the bottom of the image up to pixel $p_{i,j}$



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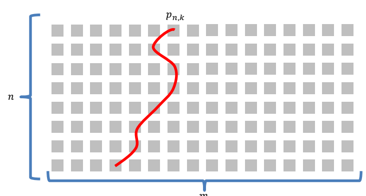
Finding the Least Energy Seam

Want the least energy seam going from bottom to top, so delete:

$$\min_{k=1}^{m}(S(n, k))$$



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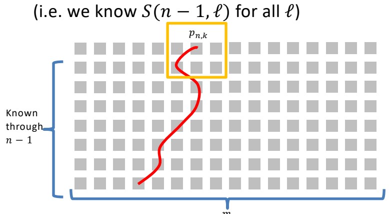
Computing $S(n, k)$

Assume we know the least energy seams for all of row $n - 1$
(i.e. we know $S(n - 1, \ell)$ for all ℓ)



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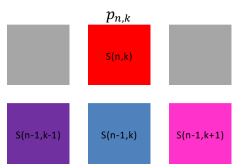
Computing $S(n,k)$

Assume we know the least energy seams for all of row $n-1$ (i.e. we know $S(n-1,\ell)$ for all ℓ)



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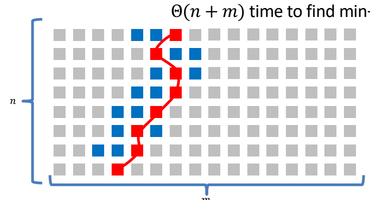
Repeated Seam Removal

Only need to update pixels dependent on the removed seam

$2n$ pixels change

$\Theta(2n)$ time to update pixels

$\Theta(n+m)$ time to find min+backtrack



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