ECS 122A: Algorithm Design and Analysis

Week 5 Discussion

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Outline

- Divide and Conquer: Key Idea
- Variant of Maximum Subarray Problem: Stock Investment
- Another Example: Binary Integer Multiplication

Divide and Conquer: Key Idea

1. **Divide** the problem into a number of subproblems that are smaller instances of the same problem.
2. **Conquer** by solving the subproblems recursively.
3. **Combine** the solutions to the subproblems to produce the solution to the original problem.

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$$T(n) = aT(n/b) + f(n)$$

So far, we demonstrated two problems that use divide and conquer paradigm:

- Merge Sort
- Maximum Subarray

We will discuss matrix-matrix multiply this Tuesday, Oct 27th.

Stock Investment

Problem Statement:

We're doing a simulation in which we look at n consecutive days of a given stock, at some point in the past. Let's number the days $i = 1, 2, ..., n$ and $p(i)$ is the price per share for the stock on that day. We want to know: When should we have bought and sold in order to have made as much money as possible?

For example, $n = 4$, $p(1) = 9$, $p(2) = 1$, $p(3) = 5, p(4) = 3$. Then we should answer "buy on day 2, sell on day 3".

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Rephrase the problem:

Input: array p of length n

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Rephrase the problem:

Input: array p of length n

Output: $\texttt{argmax}\{p(j) - p(i)\}$ where $i \leq j$

Stock Investment

Revisit maximum subarray problem:

1. Divide $A[low \cdots high]$ into two subarrays of as equal size as possible by finding the midpoint *mid*
2. Conquer:
   a. finding maximum subarrays of $A[low \cdots mid]$ and $A[mid + 1 \cdots high]$
   b. finding a max-subarray that crosses the midpoint
3. Combine: returning the max of the three

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Can we apply the same strategy on this problem?

Stock Investment

How does the conquer part work?

1. The optimal solution to $A[low \cdots mid]$
2. The optimal solution to $A[mid + 1 \cdots high]$
3. $\texttt{argmax}\{p(j) - p(i)\}$ where $low \leq i \leq mid$ and $mid + 1 \leq j \leq high$

Stock Investment

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2. The optimal solution to $A[mid + 1 \cdots high]$
3. $\texttt{argmax}\{p(j) - p(i)\}$ where $low \leq i \leq mid$ and $mid + 1 \leq j \leq high$

Time complexity:

$$\begin{aligned} T(n) &= 2T(\frac{n}{2}) + \Theta(n) + \Theta(1) \\ &= \Theta(n \log n) \end{aligned}$$

1. $2T(\frac{n}{2})$: the first two optimal solutions
2. $\Theta(n)$: the third solution is equivalent to find the `min` of $A[low \cdots mid]$ and `max` of $A[mid + 1 \cdots high]$
3. $\Theta(1)$: compare the results of three solutions

Binary Integer Multiplication

Recall how we multiply two integers of equal length $= n$

$$\begin{array}{r} 12 \\ \times\, 13 \\ \hline 36 \\ 12 \\ \hline 156 \end{array}$$

(a)

$$\begin{array}{r} 1100 \\ \times\, 1101 \\ \hline 1100 \\ 0000 \\ 1100 \\ 1100 \\ \hline 10011100 \end{array}$$

(b)

Binary Integer Multiplication

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$$
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\times\, 13 \\
\hline
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\hline
156
\end{array}
\qquad\qquad
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1100 \\
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\hline
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0000 \\
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\hline
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\end{array}
$$

(a) **(b)**

Time complexity: $O(n^2)$

1. bit multiplication: n^2
2. bit addition: $O(n)$

Binary Integer Multiplication: Speedup

First, how do we represent a decimal integer digit-wise?

$$1024 = 10^3 \times 1 + 10^2 \times 0 + 10^1 \times 1 + 10^0 \times 4$$

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Now, how about two n-bit binary integers?

$$x = \boxed{x_L}\ \boxed{x_R} = 2^{\frac{n}{2}} x_L + x_R$$
$$y = \boxed{y_L}\ \boxed{y_R} = 2^{\frac{n}{2}} y_L + y_R$$

For instance, $10110110 = \boxed{1011}\ \boxed{0110} = 2^4 \times 1011 + 0110$

$$xy = (2^{\frac{n}{2}} x_L + x_R)(2^{\frac{n}{2}} y_L + y_R) \quad = 2^n x_L y_L + 2^{\frac{n}{2}}(x_L y_R + x_R y_L) + x_R y_R$$

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Time complexity: [1]

$$T(n) = 4T(\frac{n}{2}) + \Theta(n) + \Theta(1)$$
$$= \Theta(n^2) \qquad \to \textbf{No improvement!}$$

[1] $2^n x$ is done by left shift with a constant time cost

Binary Integer Multiplication

Previously, we wrote:

$$\begin{aligned} xy &= (2^{\frac{n}{2}} x_L + x_R)(2^{\frac{n}{2}} y_L + y_R) \\ &= 2^n \underline{x_L y_L} + 2^{\frac{n}{2}}(x_L y_R + x_R y_L) + \underline{x_R y_R} \end{aligned}$$

If we rewrite

$$x_L y_R + x_R y_L = \underline{(x_L + x_R)(y_L + y_R)} - x_L y_L - x_R y_R,$$

then the entire xy will only involve three multiplications, namely the underlined parts.

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Time complexity:

$$\begin{aligned} T(n) &= 3 T(\frac{n}{2}) + \Theta(n) + \Theta(1) \\ &= \Theta(n^{\log_2 3}) \end{aligned}$$

Binary Integer Multiplication: Pseudocode

$\textsc{Multiply}(x, y)$

// x, y are positive integers of n-bit
if $n = 1$
    return xy
else
    $x_L, x_R =$ leftmost $\lceil n/2 \rceil$, rightmost $\lfloor n/2 \rfloor$ bits of x
    $y_L, y_R =$ leftmost $\lceil n/2 \rceil$, rightmost $\lfloor n/2 \rfloor$ bits of y
    $p_1 = \textsc{Multiply}(x_L, y_L)$
    $p_2 = \textsc{Multiply}(x_R, y_R)$
    $p_3 = \textsc{Multiply}(x_L + x_R, y_L + y_R)$
    return $p_1 \times 2^n + (p_3 - p_1 - p_2) \times 2^{\frac{n}{2}} + p_2$