Kartsuba's Algorithm and Linear Time Selection

Lecture 09

September 22, 2015

Part I

Fast Multiplication

Multiplying Numbers

Problem Given two $\mathbf{n}$-digit numbers $\mathbf{x}$ and $\mathbf{y}$, compute their product.

Grade School Multiplication

Compute "partial product" by multiplying each digit of $\mathbf{y}$ with $\mathbf{x}$ and adding the partial products.

$$\begin{array}{r}
3141 \\
\times 2718 \\
\hline
25128 \\
3141 \\
21987 \\
6282 \\
\hline
8537238
\end{array}$$

Time Analysis of Grade School Multiplication

1. Each partial product: $\boldsymbol{\Theta(n)}$
2. Number of partial products: $\boldsymbol{\Theta(n)}$
3. Addition of partial products: $\boldsymbol{\Theta(n^2)}$
4. Total time: $\boldsymbol{\Theta(n^2)}$

A Trick of Gauss

Carl Friedrich Gauss: 1777–1855 "Prince of Mathematicians"

Observation: Multiply two complex numbers: $(a + bi)$ and $(c + di)$

$$(a + bi)(c + di) = ac - bd + (ad + bc)i$$

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How many multiplications do we need?

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How many multiplications do we need?

Only 3! If we do extra additions and subtractions.
Compute $\mathbf{ac}, \mathbf{bd}, (\mathbf{a} + \mathbf{b})(\mathbf{c} + \mathbf{d})$. Then
$(\mathbf{ad} + \mathbf{bc}) = (\mathbf{a} + \mathbf{b})(\mathbf{c} + \mathbf{d}) - \mathbf{ac} - \mathbf{bd}$

Divide and Conquer

Assume $\mathbf{n}$ is a power of $\mathbf{2}$ for simplicity and numbers are in decimal.

Split each number into two numbers with equal number of digits

1. $\mathbf{x = x_{n-1}x_{n-2}\ldots x_0}$ and $\mathbf{y = y_{n-1}y_{n-2}\ldots y_0}$
2. $\mathbf{x = x_{n-1}\ldots x_{n/2}0\ldots 0 + x_{n/2-1}\ldots x_0}$
3. $\mathbf{x_L = 10^{n/2}x_L}$ where $\mathbf{x_L = x_{n-1}\ldots x_{n/2}}$ and $\mathbf{x_R = x_{n/2-1}\ldots x_0}$
4. Similarly $\mathbf{y = 10^{n/2}y_L + y_R}$ where $\mathbf{y_L = y_{n-1}\ldots y_{n/2}}$ and $\mathbf{y_R = y_{n/2-1}\ldots y_0}$

Example

$$\begin{aligned}
1234 \times 5678 &= (100 \times 12 + 34) \times (100 \times 56 + 78) \\
&= 10000 \times 12 \times 56 \\
&\quad +100 \times (12 \times 78 + 34 \times 56) \\
&\quad +34 \times 78
\end{aligned}$$

Divide and Conquer

Assume $\mathbf{n}$ is a power of $\mathbf{2}$ for simplicity and numbers are in decimal.

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2. $\mathbf{x} = \mathbf{10^{n/2}x_L + x_R}$ where $\mathbf{x_L} = \mathbf{x_{n-1}\ldots x_{n/2}}$ and $\mathbf{x_R} = \mathbf{x_{n/2-1}\ldots x_0}$
3. $\mathbf{y} = \mathbf{10^{n/2}y_L + y_R}$ where $\mathbf{y_L} = \mathbf{y_{n-1}\ldots y_{n/2}}$ and $\mathbf{y_R} = \mathbf{y_{n/2-1}\ldots y_0}$

Therefore

$$
\begin{aligned}
\mathbf{xy} &= \mathbf{(10^{n/2}x_L + x_R)(10^{n/2}y_L + y_R)} \\
&= \mathbf{10^n x_L y_L + 10^{n/2}(x_L y_R + x_R y_L) + x_R y_R}
\end{aligned}
$$

$T(n) = 4T(\frac{n}{2}) + 6n \quad T(1) = 1$

Time Analysis

$$\begin{aligned} xy &= (10^{n/2}x_L + x_R)(10^{n/2}y_L + y_R) \\ &= 10^n x_L y_L + 10^{n/2}(x_L y_R + x_R y_L) + x_R y_R \end{aligned}$$

4 recursive multiplications of number of size $n/2$ each plus 4 additions and left shifts (adding enough 0's to the right)

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4 recursive multiplications of number of size $n/2$ each plus 4 additions and left shifts (adding enough 0's to the right)

$$T(n) = 4T(n/2) + O(n) \qquad T(1) = O(1)$$

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$\mathbf{4}$ recursive multiplications of number of size $\mathbf{n/2}$ each plus 4 additions and left shifts (adding enough 0's to the right)

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$T(n) = \Theta(n^2)$. No better than grade school multiplication!

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$T(n) = \Theta(n^2)$. No better than grade school multiplication!

Can we invoke Gauss's trick here?

Improving the Running Time

$$\begin{aligned} xy &= (10^{n/2}x_L + x_R)(10^{n/2}y_L + y_R) \\ &= 10^n x_L y_L + 10^{n/2}(x_L y_R + x_R y_L) + x_R y_R \end{aligned}$$

Gauss trick: $x_L y_R + x_R y_L = (x_L + x_R)(y_L + y_R) - x_L y_L - x_R y_R$

$T(n) = 3T(\frac{n}{2}) + n$

Improving the Running Time

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Recursively compute only $x_L y_L, x_R y_R, (x_L + x_R)(y_L + y_R)$.

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Recursively compute only $x_L y_L, x_R y_R, (x_L + x_R)(y_L + y_R)$.

Time Analysis

Running time is given by

$$T(n) = 3T(n/2) + O(n) \qquad T(1) = O(1)$$

which means

Improving the Running Time

$$\begin{aligned} xy &= (10^{n/2}x_L + x_R)(10^{n/2}y_L + y_R) \\ &= 10^n x_L y_L + 10^{n/2}(x_L y_R + x_R y_L) + x_R y_R \end{aligned}$$

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Time Analysis

Running time is given by

$$T(n) = 3T(n/2) + O(n) \qquad T(1) = O(1)$$

which means $T(n) = O(n^{\log_2 3}) = O(n^{1.585})$

State of the Art

Schönhage-Strassen 1971: $\mathbf{O(n \log n \log \log n)}$ time using Fast-Fourier-Transform (FFT)

Martin Fürer 2007: $\mathbf{O(n \log n 2^{O(\log^* n)})}$ time

Conjecture

There is an $\mathbf{O(n \log n)}$ time algorithm.

Analyzing the Recurrences

1. Basic divide and conquer: $T(n) = 4T(n/2) + O(n)$, $T(1) = 1$. **Claim:** $T(n) = \Theta(n^2)$.
2. Saving a multiplication: $T(n) = 3T(n/2) + O(n)$, $T(1) = 1$. **Claim:** $T(n) = \Theta(n^{1+\log 1.5})$

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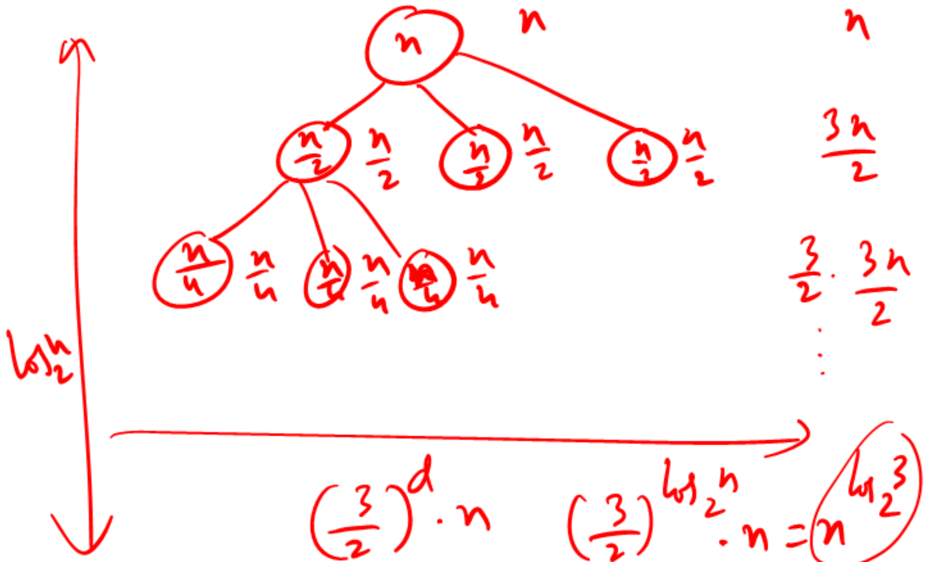
Use recursion tree method:

1. In both cases, depth of recursion $L = \log n$.
2. Work at depth i is $4^i n/2^i$ and $3^i n/2^i$ respectively: number of children at depth i times the work at each child
3. Total work is therefore $n\sum_{i=0}^{L} 2^i$ and $n\sum_{i=0}^{L}(3/2)^i$ respectively.

Recursion tree analysis



$$\left(\frac{3}{2}\right)^d \cdot n \qquad \left(\frac{3}{2}\right)^{\log_2 n} \cdot n = n^{\log_2 3}$$

Part II

Selecting in Unsorted Lists

Rank of element in an array

A: an unsorted array of **n** integers

Definition

For $\mathbf{1} \leq \mathbf{j} \leq \mathbf{n}$, element of rank **j** is the **j**'th smallest element in **A**.

Unsorted array	16	14	34	20	12	5	3	19	11
Ranks	6	5	9	8	4	2	1	7	3

Sort of array	3	5	11	12	14	16	19	20	34

Problem - Selection

Input Unsorted array $\mathbf{A}$ of $\mathbf{n}$ integers **and** integer $\mathbf{j}$

Goal Find the $\mathbf{j}$th smallest number in $\mathbf{A}$ (*rank* $\mathbf{j}$ number)

Median: $\mathbf{j} = \lfloor (\mathbf{n}+1)/2 \rfloor$

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Simplifying assumption for sake of notation: elements of $\mathbf{A}$ are distinct

Algorithm I

1. Sort the elements in $\mathbf{A}$
2. Pick $\mathbf{j}$th element in sorted order

Time taken $= \mathbf{O(n \log n)}$

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Do we need to sort? Is there an $\mathbf{O(n)}$ time algorithm?

Algorithm II

If $\mathbf{j}$ is small or $\mathbf{n - j}$ is small then

1. Find $\mathbf{j}$ smallest/largest elements in $\mathbf{A}$ in $\mathbf{O(jn)}$ time. (How?)
2. Time to find median is $\mathbf{O(n^2)}$.

Divide and Conquer Approach

1. Pick a pivot element $\mathbf{a}$ from $\mathbf{A}$
2. Partition $\mathbf{A}$ based on $\mathbf{a}$.
   $\mathbf{A}_{\mathrm{less}} = \{\mathbf{x} \in \mathbf{A} \mid \mathbf{x} \leq \mathbf{a}\}$ and $\mathbf{A}_{\mathrm{greater}} = \{\mathbf{x} \in \mathbf{A} \mid \mathbf{x} > \mathbf{a}\}$
3. $|\mathbf{A}_{\mathrm{less}}| = \mathbf{j}$: return $\mathbf{a}$
4. $|\mathbf{A}_{\mathrm{less}}| > \mathbf{j}$: recursively find $\mathbf{j}$th smallest element in $\mathbf{A}_{\mathrm{less}}$
5. $|\mathbf{A}_{\mathrm{less}}| < \mathbf{j}$: recursively find $\mathbf{k}$th smallest element in $\mathbf{A}_{\mathrm{greater}}$ where $\mathbf{k} = \mathbf{j} - |\mathbf{A}_{\mathrm{less}}|$.

Example

16	14	34	20	12	5	3	19	11

$j = 8$

14, 5, 3, 12, 11 16 20 34 19

6

Time Analysis

1. Partitioning step: $\mathbf{O(n)}$ time to scan $\mathbf{A}$
2. How do we choose pivot? Recursive running time?

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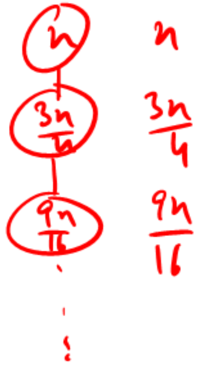
Suppose we always choose pivot to be $\mathbf{A[1]}$.

Say $\mathbf{A}$ is sorted in increasing order and $\mathbf{j = n}$.
Exercise: show that algorithm takes $\mathbf{\Omega(n^2)}$ time

A Better Pivot

Suppose pivot is the ℓth smallest element where $\mathbf{n/4 \le \ell \le 3n/4}$. That is pivot is *approximately* in the middle of $\mathbf{A}$
Then $\mathbf{n/4} \le |\mathbf{A}_{\text{less}}| \le \mathbf{3n/4}$ *and* $\mathbf{n/4} \le |\mathbf{A}_{\text{greater}}| \le \mathbf{3n/4}$. If we apply recursion,

$$T(n) \le n + T\left(\frac{3n}{4}\right)$$



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$$\mathbf{T(n) \leq T(3n/4) + O(n)}$$

Implies $\mathbf{T(n) = O(n)}$!

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Analysis a little bit later.

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Can we choose pivot deterministically?

Idea

1. Break input $\mathbf{A}$ into many subarrays: $\mathbf{L_1, \ldots L_k}$.
2. Find median $\mathbf{m_i}$ in each subarray $\mathbf{L_i}$.
3. Find the median $\mathbf{x}$ of the medians $\mathbf{m_1, \ldots, m_k}$.
4. Intuition: The median $\mathbf{x}$ should be close to being a good median of all the numbers in $\mathbf{A}$.
5. Use $\mathbf{x}$ as pivot in previous algorithm.

Example

11	7	3	42	174	310	1	92	87	12	19	15

7 174 87 15

$\frac{n}{3}$

15

Choosing the pivot

A clash of medians

1. Partition array $\mathbf{A}$ into $\lceil \mathbf{n}/\mathbf{5} \rceil$ lists of $\mathbf{5}$ items each.
   $\mathbf{L_1 = \{A[1], A[2], \ldots, A[5]\}}$, $\mathbf{L_2 = \{A[6], \ldots, A[10]\}}$, $\ldots$,
   $\mathbf{L_i = \{A[5i+1], \ldots, A[5i-4]\}}$, $\ldots$,
   $\mathbf{L_{\lceil n/5 \rceil} = \{A[5\lceil n/5 \rceil - 4, \ldots, A[n]\}}$.
2. For each $\mathbf{i}$ find median $\mathbf{b_i}$ of $\mathbf{L_i}$ using brute-force in $\mathbf{O(1)}$ time. Total $\mathbf{O(n)}$ time
3. Let $\mathbf{B = \{b_1, b_2, \ldots, b_{\lceil n/5 \rceil}\}}$
4. Find median $\mathbf{b}$ of $\mathbf{B}$

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Lemma

Median of $\mathbf{B}$ *is an* approximate *median of* $\mathbf{A}$. *That is, if* $\mathbf{b}$ *is used a pivot to partition* $\mathbf{A}$, *then* $|\mathbf{A}_{less}| \leq \mathbf{7n/10 + 6}$ and $|\mathbf{A}_{greater}| \leq \mathbf{7n/10 + 6}$.

Algorithm for Selection

A storm of medians

```
select(A, j):
    Form lists L_1, L_2, ..., L_⌈n/5⌉ where L_i = {A[5i − 4], ..., A[5i]}
    Find median b_i of each L_i using brute-force
    Find median b of B = {b_1, b_2, ..., b_⌈n/5⌉}
    Partition A into A_less and A_greater using b as pivot
    if (|A_less|) = j return b
    else if (|A_less|) > j)
        return select(A_less, j)
    else
        return select(A_greater, j − |A_less|)
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How do we find median of **B**? Recursively!

```
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    Form lists L_1, L_2, ..., L_⌈n/5⌉ where L_i = {A[5i − 4], ..., A[5i]}
    Find median b_i of each L_i using brute-force
    B = [b_1, b_2, ..., b_⌈n/5⌉]
    b = select(B, ⌈n/10⌉)
    Partition A into A_less and A_greater using b as pivot
    if (|A_less|) = j return b
    else if (|A_less|) > j)
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Running time of deterministic median selection

A dance with recurrences

$$\mathbf{T(n) = T(\lceil n/5 \rceil) + \max\{T(|A_{less}|), T(|A_{greater})|\} + O(n)}$$

Running time of deterministic median selection

A dance with recurrences

$$T(n) = T(\lceil n/5 \rceil) + \max\{T(|A_{\text{less}}|), T(|A_{\text{greater}})|\} + O(n)$$

From Lemma,

$$T(n) \leq T(\lceil n/5 \rceil) + T(\lfloor 7n/10 + 6 \rfloor) + O(n)$$

and

$$T(n) = O(1) \qquad n < 10$$

Running time of deterministic median selection

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Exercise: show that $T(n) = O(n)$

Median of Medians: Proof of Lemma

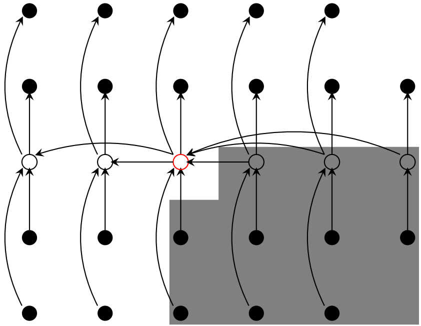

Figure : Shaded elements are all greater than **b**

Proposition

There are at least $\mathbf{3n/10 - 6}$ *elements greater than the median of medians* **b**.

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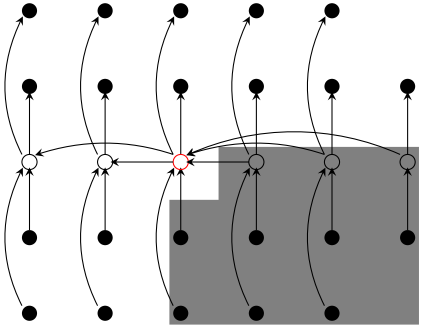

Figure : Shaded elements are all greater than $\mathbf{b}$

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There are at least $\mathbf{3n/10 - 6}$ *elements greater than the median of medians* $\mathbf{b}$*.*

Proof.

At least half of the $\lceil \mathbf{n/5} \rceil$ groups have at least 3 elements larger than $\mathbf{b}$, except for last group and the group containing $\mathbf{b}$. Hence number of elements greater than $\mathbf{b}$ is:

$$\mathbf{3(\lceil (1/2)\lceil n/5 \rceil \rceil - 2) \geq 3n/10 - 6}$$

$\square$

Median of Medians: Proof of Lemma

Proposition

There are at least $\mathbf{3n/10 - 6}$ *elements greater than the median of medians* $\mathbf{b}$.

Corollary

$|\mathbf{A}_{less}| \leq \mathbf{7n/10 + 6}$.

Via symmetric argument,

Corollary

$|\mathbf{A}_{greater}| \leq \mathbf{7n/10 + 6}$.

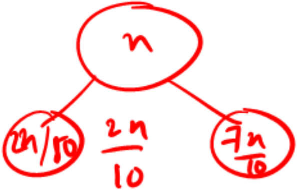
Questions to ponder

1. Why did we choose lists of size **5**? Will lists of size **3** work?
2. Write a recurrence to analyze the algorithm's running time if we choose a list of size **k**.

n

$\frac{9n}{10}$

$\frac{9}{10} \cdot \frac{9}{10} n$



n

$\frac{7n}{10}$

$$T(n) = T\left(\frac{9n}{10}\right) + n$$

Median of Medians Algorithm

Due to:

M. Blum, R. Floyd, D. Knuth, V. Pratt, R. Rivest, and R. Tarjan.
"Time bounds for selection".
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All except Vaughn Pratt!

Takeaway Points

1. Recursion tree method and guess and verify are the most reliable methods to analyze recursions in algorithms.
2. Recursive algorithms naturally lead to recurrences.
3. Some times one can look for certain type of recursive algorithms (reverse engineering) by understanding recurrences and their behavior.