Recurrences, and Linear Time Selection

Lecture 12
March 3, 2015
Solving Recurrences

Two general methods:

1. Recursion tree method: need to do sums
   1. elementary methods, geometric series
   2. integration

2. Guess and Verify
   1. guessing involves intuition, experience and trial & error
   2. verification is via induction
Consider $T(n) = 2T(n/2) + n/\log n$. 

\[
\begin{align*}
    T(2) &= 1 \\
    \frac{n}{\log n} \\
    \frac{n}{2 \log \frac{n}{2}} \\
    \frac{n}{4} \\
    \frac{n}{2 \log \frac{n}{4}} \\
    \frac{n}{4} \\
    \frac{n}{4} \\
    \frac{n}{4} \\
    \frac{n}{4} \\
    = n \log \log n \\
    \frac{2}{\log n} + \frac{n}{\log n - 1} + \frac{n}{\log n - \frac{1}{2}} + \ldots + \frac{n}{1} &= n \left( \frac{1}{\log n} + \frac{1}{\log n - 1} + \frac{1}{\log n - \frac{1}{2}} + \ldots + \frac{1}{1} \right)
\end{align*}
\]
1. Consider $T(n) = 2T(n/2) + n/\log n$.
2. Construct recursion tree, and observe pattern.
Consider $T(n) = 2T(n/2) + n/\log n$.

Construct recursion tree, and observe pattern. $i$th level has $2^i$ nodes, and problem size at each node is $n/2^i$ and hence work at each node is $\frac{n}{2^i}/\log\frac{n}{2^i}$. 
Consider $T(n) = 2T(n/2) + n/\log n$.

Construct recursion tree, and observe pattern. $i$th level has $2^i$ nodes, and problem size at each node is $n/2^i$ and hence work at each node is $\frac{n}{2^i}/\log \frac{n}{2^i}$.

Summing over all levels

$$T(n) = \sum_{i=0}^{\log n - 1} 2^i \left[ \frac{(n/2^i)}{\log(n/2^i)} \right]$$

$$= \sum_{i=0}^{\log n - 1} \frac{n}{\log n - i}$$

$$= n \sum_{j=1}^{\log n} \frac{1}{j} = n H_{\log n} = \Theta(n \log \log n)$$
Consider \( T(n) = T(\sqrt{n}) + 1 \)

Number of levels: \( \sqrt{n}, \sqrt{\sqrt{n}}, \sqrt{\sqrt{\sqrt{n}}}, ..., O(1) \)

Number of children at each level is 1, work at each node is 1.

Thus, \( T(n) = \sum_{i=0}^{L} 1 = \Theta(L) = \Theta(\log \log n) \).
Recurrence: Example II

1. Consider $T(n) = T(\sqrt{n}) + 1$

2. What is the depth of recursion?

$\sqrt{n}, \sqrt[4]{n}, \sqrt[8]{n}, \ldots, O(1)$.
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What is the depth of recursion?
\( \sqrt{n}, \sqrt{\sqrt{n}}, \sqrt{\sqrt{\sqrt{n}}}, \ldots, O(1). \)

Number of levels: \( n^{2^{-L}} = 2 \) means \( L = \log \log n \).
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What is the depth of recursion? $\sqrt{n}$, $\sqrt{\sqrt{n}}$, $\sqrt{\sqrt{\sqrt{n}}}$, ..., $O(1)$.

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Thus, $T(n) = \sum_{i=0}^{L} 1 = \Theta(L) = \Theta(\log \log n)$. 
Consider \( T(n) = \sqrt{n}T(\sqrt{n}) + n \).
1. Consider $T(n) = \sqrt{n}T(\sqrt{n}) + n$.

2. Using recursion trees: number of levels $L = \log \log n$. 

Thus, $T(n) = \Theta(n \log \log n)$. 

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1 Consider \( T(n) = \sqrt{n}T(\sqrt{n}) + n \).

2 Using recursion trees: number of levels \( L = \log \log n \)

3 Work at each level? Root is \( n \), next level is \( \sqrt{n} \times \sqrt{n} = n \).
   Can check that each level is \( n \).

Thus, \( T(n) = \Theta(n \log \log n) \)
1. Consider $T(n) = \sqrt{n}T(\sqrt{n}) + n$.
2. Using recursion trees: number of levels $L = \log \log n$.
3. Work at each level? Root is $n$, next level is $\sqrt{n} \times \sqrt{n} = n$. Can check that each level is $n$.
4. Thus, $T(n) = \Theta(n \log \log n)$.
Consider $T(n) = T(n/4) + T(3n/4) + n$. Using recursion tree, we observe the tree has leaves at different levels (a lop-sided tree). Total work in any level is at most $n$. Total work in any level without leaves is exactly $n$. Highest leaf is at level $\log_4 n$ and lowest leaf is at level $\log_4 \frac{3n}{4}$. Thus, $n \log_4 n \leq T(n) \leq n \log_4 \frac{3n}{4}$, which means $T(n) = \Theta(n \log n)$. 

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Thus, $n \log_4 n \leq T(n) \leq n \log_{4/3} n$, which means $T(n) = \Theta(n \log n)$.
Recurrence: Example IV

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Highest leaf is at level $\log_4 n$ and lowest leaf is at level $\log_{4/3} n$.
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Part II

Selecting in Unsorted Lists
Quick Sort

Quick Sort [Hoare]

1. Pick a pivot element from array
2. Split array into 3 subarrays: those smaller than pivot, those larger than pivot, and the pivot itself.
3. Recursively sort the subarrays, and concatenate them.
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3. Recursively sort the subarrays, and concatenate them.

Example:

1. array: 16, 12, 14, 20, 5, 3, 18, 19, 1
2. pivot: 16
3. split into 12, 14, 5, 3, 1 and 20, 19, 18 and recursively sort
4. put them together with pivot in middle
Quick Sort [Hoare]

1. Pick a pivot element from array
2. Split array into 3 subarrays: those smaller than pivot, those larger than pivot, and the pivot itself. Linear scan of array does it. Time is $O(n)$
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3. split into 12, 14, 5, 3, 1 and 20, 19, 18 and recursively sort
4. put them together with pivot in middle
Let $k$ be the rank of the chosen pivot. Then,

$$T(n) = T(k - 1) + T(n - k) + O(n)$$
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\]

If \( k = \lceil n/2 \rceil \) then
\[
T(n) = T(\lceil n/2 \rceil - 1) + T(\lfloor n/2 \rfloor) + O(n) \leq 2T(n/2) + O(n).
\]
Then, \( T(n) = O(n \log n) \).
Time Analysis

1. Let \( k \) be the rank of the chosen pivot. Then,
\[
T(n) = T(k - 1) + T(n - k) + O(n)
\]

2. If \( k = \lceil n/2 \rceil \) then
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T(n) = T(\lceil n/2 \rceil - 1) + T(\lfloor n/2 \rfloor) + O(n) \leq 2T(n/2) + O(n)
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1. Theoretically, median can be found in linear time.
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$$T(n) = T(k - 1) + T(n - k) + O(n)$$

If $k = \lceil n/2 \rceil$ then
$$T(n) = T(\lceil n/2 \rceil - 1) + T(\lfloor n/2 \rfloor) + O(n) \leq 2T(n/2) + O(n).$$
Then, $T(n) = O(n \log n)$.

Theoretically, median can be found in linear time.

Typically, pivot is the first or last element of array. Then,
$$T(n) = \max_{1 \leq k \leq n} (T(k - 1) + T(n - k) + O(n))$$

In the worst case $T(n) = T(n - 1) + O(n)$, which means $T(n) = O(n^2)$. Happens if array is already sorted and pivot is always first element.
Consider an algorithm \textit{alg} that is given an input of size \( n \). In \( O(n) \) time, it either solves the problem, or solve it by calling recursively on an input of size, say, \( \leq (15/16)n \). The running time of \textit{alg} is

(A) \( O(n^2) \)
(B) \( O(n \log n) \)
(C) \( O(n) \)
(D) There are not enough details.
Problem - Selection

Input  Unsorted array $A$ of $n$ integers

Goal   Find the $j$th smallest number in $A$ (rank $j$ number)

Example

$A = \{4, 6, 2, 1, 5, 8, 7\}$ and $j = 4$. The $j$th smallest element is 5.

Median: $j = \lfloor (n + 1)/2 \rfloor$
Problem - Selection

Input  Unsorted array \( A \) of \( n \) integers

Goal  Find the \( j \)th smallest number in \( A \) (rank \( j \) number)

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Median: \( j = \lfloor (n + 1)/2 \rfloor \)

Simplifying assumption for sake of notation: elements of \( A \) are distinct

\[ 4, 6, 2, 1, 5, 7, 8 \]

\[ 1, 2, 4, 6, 5, 7, 8 \]
Algorithm I

1. Sort the elements in A
2. Pick $j$th element in sorted order

Time taken = $O(n \log n)$
Algorithm 1

1. Sort the elements in $A$
2. Pick $j$th element in sorted order

Time taken $= O(n \log n)$

Do we need to sort? Is there an $O(n)$ time algorithm?
Algorithm II

If $j$ is small or $n - j$ is small then

1. Find $j$ smallest/largest elements in $A$ in $O(jn)$ time. (How?)
2. Time to find median is $O(n^2)$. 
Divide and Conquer Approach

1. Pick a pivot element \( a \) from \( A \)
2. Partition \( A \) based on \( a \).
   \[ A_{\text{less}} = \{ x \in A \mid x \leq a \} \quad \text{and} \quad A_{\text{greater}} = \{ x \in A \mid x > a \} \]
3. \( |A_{\text{less}}| = j \): return \( a \)
4. \( |A_{\text{less}}| > j \): recursively find \( j \)th smallest element in \( A_{\text{less}} \)
5. \( |A_{\text{less}}| < j \): recursively find \( k \)th smallest element in \( A_{\text{greater}} \)
   where \( k = j - |A_{\text{less}}| \).
Time Analysis

1. Partitioning step: $O(n)$ time to scan $A$
2. How do we choose pivot? Recursive running time?
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Time Analysis

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2. How do we choose pivot? Recursive running time?

Suppose we always choose pivot to be \( A[1] \).

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

Suppose pivot is the $\ell$th smallest element where $\frac{n}{4} \leq \ell \leq \frac{3n}{4}$. That is pivot is *approximately* in the middle of $A$

Then $\frac{n}{4} \leq |A_{\text{less}}| \leq \frac{3n}{4}$ and $\frac{n}{4} \leq |A_{\text{greater}}| \leq \frac{3n}{4}$. If we apply recursion,

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

implies $T(n) = O(n)$! How do we find such a pivot? Randomly? In fact, it works! Analysis a little bit later.

Can we choose pivot deterministically?

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A Better Pivot

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Implies $T(n) = O(n)$!

How do we find such a pivot? Randomly? In fact works! Analysis a little bit later.

Can we choose pivot deterministically?
Divide and Conquer Approach
A game of medians

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

But we have to be...
More specific...
1. Size of each group?
2. How to find median of medians?
Choosing the pivot
A clash of medians

1. Partition array $A$ into $\lceil n/5 \rceil$ lists of 5 items each.

$L_1 = \{A[1], A[2], \ldots, A[5]\}, L_2 = \{A[6], \ldots, A[10]\}, \ldots,$
$L_i = \{A[5i + 1], \ldots, A[5i - 4]\}, \ldots,$
$L_{\lceil n/5 \rceil} = \{A[5\lceil n/5 \rceil - 4, \ldots, A[n]\}.

2. For each $i$ find median $b_i$ of $L_i$ using brute-force in $O(1)$ time.

Total $O(n)$ time

3. Let $B = \{b_1, b_2, \ldots, b_{\lceil n/5 \rceil}\}$

4. Find median $b$ of $B$
Choosing the pivot
A clash of medians

1. Partition array $A$ into $\left\lceil n/5 \right\rceil$ lists of 5 items each.
   $L_1 = \{A[1], A[2], \ldots, A[5]\}$, $L_2 = \{A[6], \ldots, A[10]\}$, \ldots,
   $L_i = \{A[5i + 1], \ldots, A[5i - 4]\}$, \ldots,
   $L_{\left\lceil n/5 \right\rceil} = \{A[5\left\lceil n/5 \right\rceil - 4], \ldots, A[n]\}$.

2. For each $i$ find median $b_i$ of $L_i$ using brute-force in $O(1)$ time.
   Total $O(n)$ time

3. Let $B = \{b_1, b_2, \ldots, b_{\left\lceil n/5 \right\rceil}\}$

4. Find median $b$ of $B$

Lemma

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

A storm of medians

\textbf{Algorithm for Selection}

\textbf{select}(A, j):

Form lists \( L_1, L_2, \ldots, L_{\lceil n/5 \rceil} \) where \( L_i = \{A[5i - 4], \ldots, A[5i]\} \)

Find median \( b_i \) of each \( L_i \) using brute-force

Find median \( b \) of \( B = \{b_1, b_2, \ldots, b_{\lceil n/5 \rceil}\} \)

 Partition \( A \) into \( A_{\text{less}} \) and \( A_{\text{greater}} \) using \( b \) as pivot

\textbf{if} \ (|A_{\text{less}}|) = j \ \textbf{return} \ b

\textbf{else if} \ (|A_{\text{less}}|) > j

\textbf{return} \ select(A_{\text{less}}, j)

\textbf{else}

\textbf{return} \ select(A_{\text{greater}}, j - |A_{\text{less}}|)
Algorithm for Selection
A storm of medians

\[ \text{select}(A, j): \]
- Form lists \( L_1, L_2, \ldots, L_{\lceil n/5 \rceil} \) where \( L_i = \{A[5i-4], \ldots, A[5i]\} \)
- Find median \( b_i \) of each \( L_i \) using brute-force
- Find median \( b \) of \( B = \{b_1, b_2, \ldots, b_{\lceil n/5 \rceil}\} \)
- Partition \( A \) into \( A_{\text{less}} \) and \( A_{\text{greater}} \) using \( b \) as pivot
  - if \( (|A_{\text{less}}|) = j \) return \( b \)
  - else if \( (|A_{\text{less}}|) > j \)
    - return \( \text{select}(A_{\text{less}}, j) \)
  - else
    - return \( \text{select}(A_{\text{greater}}, j - |A_{\text{less}}|) \)

How do we find median of \( B \)?
select$(A, j)$:
Form lists $L_1, L_2, \ldots, L_{\lceil n/5 \rceil}$ where $L_i = \{A[5i - 4], \ldots, A[5i]\}$
Find median $b_i$ of each $L_i$ using brute-force
Find median $b$ of $B = \{b_1, b_2, \ldots, b_{\lceil n/5 \rceil}\}$
Partition $A$ into $A_{\text{less}}$ and $A_{\text{greater}}$ using $b$ as pivot
if ($|A_{\text{less}}| = j$) return $b$
else if ($|A_{\text{less}}| > j$)
    return select$(A_{\text{less}}, j)$
else
    return select$(A_{\text{greater}}, j - |A_{\text{less}}|)$

How do we find median of $B$? Recursively!
Algorithm for Selection
A storm of medians

\textbf{select}(A, j):

Form lists \( L_1, L_2, \ldots, L_{\lceil n/5 \rceil} \) where \( L_i = \{A[5i - 4], \ldots, A[5i]\} \)
Find median \( b_i \) of each \( L_i \) using brute-force
\( B = [b_1, b_2, \ldots, b_{\lceil n/5 \rceil}] \)
\( b = \text{select}(B, \lceil n/10 \rceil) \)
Partition \( A \) into \( A_{\text{less}} \) and \( A_{\text{greater}} \) using \( b \) as pivot
\textbf{if} (\( |A_{\text{less}}| \)) = \( j \) \textbf{return} \( b \)
\textbf{else if} (\( |A_{\text{less}}| \)) > \( j \)
\hspace{1em} \textbf{return} \text{select}(A_{\text{less}}, \ j)
\textbf{else}
\hspace{1em} \textbf{return} \text{select}(A_{\text{greater}}, \ j - |A_{\text{less}}|)
Running time of deterministic median selection

A dance with recurrences

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

\[ T(n) = O(1) \quad n < 10 \]
Running time of deterministic median selection
A dance with recurrences

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From Lemma,

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

and

\[ T(n) = O(1) \quad n < 10 \]

Exercise: show that \( T(n) = O(n) \)
Proposition

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

Figure: Shaded elements are all greater than $b$. 
Median of Medians: Proof of Lemma

**Proposition**

There are at least \( \frac{3n}{10} - 6 \) elements greater than the median of medians \( b \).

**Proof.**

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

\[
3 \left( \left\lceil \frac{1}{2} \right\rceil \left\lceil \frac{n}{5} \right\rceil - 2 \right) \geq \frac{3n}{10} - 6
\]

Figure: Shaded elements are all greater than \( b \)
Proposition

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

Corollary

$|A_{\text{less}}| \leq \frac{7n}{10} + 6$.

Via symmetric argument,

Corollary

$|A_{\text{greater}}| \leq \frac{7n}{10} + 6$. 
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 $k$. 
Median of Medians Algorithm

Due to:
“Time bounds for selection”.
Median of Medians Algorithm

Due to:
“Time bounds for selection”.

How many Turing Award winners in the author list?
Median of Medians Algorithm

Due to:
“Time bounds for selection”.

How many Turing Award winners in the author list?
All except Vaughn Pratt!
Part III

Exponentiation, Binary Search
Input  Two numbers:  \( a \) and integer \( n \geq 0 \)

Goal  Compute \( a^n \)
Exponentiation

Input  Two numbers: $a$ and integer $n \geq 0$

Goal  Compute $a^n$

Obvious algorithm:

$$\textbf{SlowPow}(a,n):$$

\begin{align*}
    & x = 1; \\
    & \text{for } i = 1 \text{ to } n \text{ do} \\
    & \quad x = x \times a \\
    & \text{Output } x
\end{align*}

$O(n)$ multiplications.
Let $a > 1$ and $n > 1$ be two integer numbers. Representing $a^n$ in base 2 requires

(A) $O(\log a + \log n)$ bits.
(B) $O(n \log a)$ bits.
(C) $O(a \log n)$ bits.
(D) $O(\log a \log n)$ bits.
(E) $O\left((\log a)^{\log n}\right)$ bits.
Observation: \( a^n = a^{\lfloor n/2 \rfloor} a^{\lceil n/2 \rceil} = a^{\lfloor n/2 \rfloor} a^{\lfloor n/2 \rfloor} a^{\lfloor n/2 \rfloor - \lfloor n/2 \rfloor} \).
Observation: \( a^n = a^{\lfloor n/2 \rfloor} a^{\lceil n/2 \rceil} = a^{\lfloor n/2 \rfloor} a^{\lfloor n/2 \rfloor} a^{\lceil n/2 \rceil} - \lfloor n/2 \rfloor \).

**FastPow\((a, n)\):**

if \((n = 0)\) return 1

\(x = \text{FastPow}(a, \lfloor n/2 \rfloor)\)

\(x = x \times x\)

if \((n\) is odd) then

\(x = x \times a\)

return \(x\)
Fast Exponentiation

Observation: \( a^n = a^{\lfloor n/2 \rfloor} a^{\lceil n/2 \rceil} = a^{\lfloor n/2 \rfloor} a^{\lceil n/2 \rceil} a^{\lfloor n/2 \rfloor} - \lfloor n/2 \rfloor} \).

\( \text{FastPow}(a, n) : \)

if (n = 0) return 1

x = \text{FastPow}(a, \lfloor n/2 \rfloor)

x = x \times x

if (n is odd) then
    x = x \times a

return x

\( T(n) : \) number of multiplications for \( n \)
Fast Exponentiation

Observation: $a^n = a^{\lfloor n/2 \rfloor} a^{\lceil n/2 \rceil} = a^{\lfloor n/2 \rfloor} a^{\lfloor n/2 \rfloor} a^{\lfloor n/2 \rfloor - [n/2]}$.

**FastPow** $(a,n)$:
- if $(n = 0)$ return 1
- $x = \text{FastPow}(a, \lfloor n/2 \rfloor)$
- $x = x \times x$
- if $(n \text{ is odd})$ then
  - $x = x \times a$
- return $x$

$T(n)$: number of multiplications for $n$

$$T(n) \leq T(\lfloor n/2 \rfloor) + 2$$

$T(n) =$
Fast Exponentiation

Observation: \( a^n = a^{\lfloor n/2 \rfloor} a^{\lceil n/2 \rceil} = a^{\lfloor n/2 \rfloor} a^{\lfloor n/2 \rfloor} a^{\lceil n/2 \rceil - \lfloor n/2 \rfloor} \).

**FastPow** \((a, n)\):

- if \((n = 0)\) return 1
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  - \(x = x \times a\)
- return \(x\)

\(T(n)\): number of multiplications for \(n\)

\[ T(n) \leq T(\lfloor n/2 \rfloor) + 2 \]

\(T(n) = \Theta(\log n)\)
Question: Is \textit{SlowPow()} a polynomial time algorithm? \textit{FastPow}?
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Input size: $O(\log a + \log n)$
Complexity of Exponentiation

**Question:** Is \texttt{SlowPow()} a polynomial time algorithm? \texttt{FastPow}?

Input size: \(O(\log a + \log n)\)

Output size:
Complexity of Exponentiation

Question: Is \textbf{SlowPow()} a polynomial time algorithm? \textbf{FastPow}?  
Input size: \(O(\log a + \log n)\)  
Output size: \(O(n \log a)\).

Not necessarily polynomial in input size!

Both \textbf{SlowPow} and \textbf{FastPow} are polynomial in output size.
26 mod 7 is?

(A) 0
(B) 1
(C) 3
(D) 5
(E) 7
Exponentiation modulo a given number

Exponentiation in applications:

Input  Three integers: $a, n \geq 0, p \geq 2$ (typically a prime)
Goal   Compute $a^n \mod p$
Exponentiation modulo a given number

Exponentiation in applications:

Input: Three integers: \( a, n \geq 0, p \geq 2 \) (typically a prime)

Goal: Compute \( a^n \mod p \)

Input size: \( \Theta(\log a + \log n + \log p) \)

Output size: \( O(\log p) \) and hence polynomial in input size.
Exponentiation in applications:

**Input** Three integers: \( a, n \geq 0, p \geq 2 \) (typically a prime)

**Goal** Compute \( a^n \mod p \)

Input size: \( \Theta(\log a + \log n + \log p) \)

Output size: \( O(\log p) \) and hence polynomial in input size.

**Observation:** \( xy \mod p = ((x \mod p)(y \mod p)) \mod p \)
Exponentiation modulo a given number

Input  Three integers:  \( a, n \geq 0, p \geq 2 \) (typically a prime)

Goal  Compute \( a^n \mod p \)

**FastPowMod**\( (a, n, p) \):

- if \( n = 0 \) return 1
- \( x = \text{FastPowMod}(a, \lfloor n/2 \rfloor, p) \)
- \( x = x \times x \mod p \)
- if (\( n \) is odd)
  - \( x = x \times a \mod p \)

return \( x \)
Exponentiation modulo a given number

Input  Three integers:  \( a, n \geq 0, p \geq 2 \) (typically a prime)

Goal  Compute \( a^n \mod p \)

**FastPowMod** \((a,n,p)\):

- if \((n = 0)\) return 1
- \(x = \text{FastPowMod}(a, \lfloor n/2 \rfloor, p)\)
- \(x = x \times x \mod p\)
- if \((n \text{ is odd})\)
  - \(x = x \times a \mod p\)

return \(x\)

**FastPowMod** is a polynomial time algorithm. **SlowPowMod** is not (why?).
Input  Sorted array $A$ of $n$ numbers and number $x$
Goal  Is $x$ in $A$?

Binary Search in Sorted Arrays

```plaintext
BinarySearch(A[a..b], x):
  if (b−a < 0) return NO
  mid = A[⌊(a + b)/2⌋]
  if (x = mid) return YES
  if (x < mid) return BinarySearch(A[a..⌊(a + b)/2⌋−1], x)
  else return BinarySearch(A[⌊(a + b)/2⌋+ 1..b], x)
```

Analysis:
$T(n) = T(⌊n/2⌋) + O(1)$.
$T(n) = O(\log n)$.

Observation:
After $k$ steps, size of array left is $n/2^k$. 

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Binary Search in Sorted Arrays

Input  Sorted array $A$ of $n$ numbers and number $x$
Goal  Is $x$ in $A$?

**BinarySearch**($A[a..b]$, $x$):
  
  if ($b - a < 0$) return NO
  
  mid = $A[\lfloor(a + b)/2\rfloor]$
  
  if ($x = \text{mid}$) return YES
  
  if ($x < \text{mid}$)
    return BinarySearch($A[a..\lfloor(a + b)/2\rfloor - 1]$, $x$)
  
  else
    return BinarySearch($A[\lfloor(a + b)/2\rfloor + 1..b]$, $x$)

Analysis:

$T(n) = T(\lfloor n/2 \rfloor) + O(1)$.

$T(n) = O(\log n)$.

Observation:

After $k$ steps, size of array left is $n/2^k$.
Binary Search in Sorted Arrays

Input  Sorted array \( A \) of \( n \) numbers and number \( x \)

Goal  Is \( x \) in \( A \)?

\[
\text{BinarySearch}(A[a..b], x) :
\]
\[
\text{if } (b - a < 0) \text{ return NO}
\]
\[
\text{mid} = A[\lfloor (a + b)/2 \rfloor]
\]
\[
\text{if } (x = \text{mid}) \text{ return YES}
\]
\[
\text{if } (x < \text{mid})
\]
\[
\text{return BinarySearch}(A[a..\lfloor (a + b)/2 \rfloor - 1], x)
\]
\[
\text{else}
\]
\[
\text{return BinarySearch}(A[\lfloor (a + b)/2 \rfloor + 1..b], x)
\]

Analysis: \( T(n) = T(\lfloor n/2 \rfloor) + O(1) \). \( T(n) = O(\log n) \).

Observation: After \( k \) steps, size of array left is \( n/2^k \).
Another common use of binary search

1. **Optimization version**: find solution of best (say minimum) value
2. **Decision version**: is there a solution of value at most a given value $v$?

- Given instance $I$, compute upper bound $U(I)$ on best value
- Compute lower bound $L(I)$ on best value
- Do binary search on interval $[L(I), U(I)]$ using decision version as black box
- $O(\log(U(I) - L(I)))$ calls to decision version if $U(I)$, $L(I)$ are integers
Another common use of binary search

1. **Optimization version:** find solution of best (say minimum) value
2. **Decision version:** is there a solution of value at most a given value \( v \)?

Reduce optimization to decision (may be easier to think about):

1. Given instance \( I \) compute upper bound \( U(I) \) on best value
2. Compute lower bound \( L(I) \) on best value
3. Do binary search on interval \([L(I), U(I)]\) using decision version as black box
4. \( O(\log(U(I) - L(I))) \) calls to decision version if \( U(I), L(I) \) are integers
Example

1. **Problem:** shortest paths in a graph.

2. **Decision version:** given $G$ with non-negative integer edge lengths, nodes $s$, $t$ and bound $B$, is there an $s$-$t$ path in $G$ of length at most $B$?

3. **Optimization version:** find the length of a shortest path between $s$ and $t$ in $G$.

**Question:** given a black box algorithm for the decision version, can we obtain an algorithm for the optimization version?
Example continued

Question: given a black box algorithm for the decision version, can we obtain an algorithm for the optimization version?

1. Let $U$ be maximum edge length in $G$.
2. Minimum edge length is $L$.
3. $s$-$t$ shortest path length is at most $(n - 1)U$ and at least $L$.
5. $O(\log((n - 1)U - L))$ calls to the decision problem algorithm sufficient. Polynomial in input size.
**Question**

\( G = (V, E) \) is a directed graph with non-negative edge lengths; \( \ell(e) \) length of edge \( e \). Want to find cycle \( C \) to minimize \( \ell(C)/|C| \), that is, the average length of the cycle.

Recall discussion question: given \( \lambda \) can reduce checking whether \( G \) has cycle of average length \( \leq \lambda \) to negative cycle detection.

**Question:** Suppose we do binary search using the preceding algorithm to find the minimize the average length of a cycle? What is the search range? How many times do we need to call the algorithm for negative cycle detection?
Part IV

Closest Pair
Closest Pair - the problem

Input  Given a set $S$ of $n$ points on the plane
Goal  Find $p, q \in S$ such that $d(p, q)$ is minimum
Closest Pair - the problem

**Input**  Given a set $S$ of $n$ points on the plane

**Goal**  Find $p, q \in S$ such that $d(p, q)$ is minimum
Applications

1. Basic primitive used in graphics, vision, molecular modelling
2. Ideas used in solving nearest neighbor, Voronoi diagrams, Euclidean MST
Algorithm: Brute Force

1. Compute distance between every pair of points and find minimum.
2. Takes $O(n^2)$ time.
3. Can we do better?
Algorithm: Brute Force

1. Compute distance between every pair of points and find minimum.
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Algorithm: Brute Force

1. Compute distance between every pair of points and find minimum.
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3. Can we do better?
Closest Pair: 1-d case

**Input**  Given a set \( S \) of \( n \) points on a line

**Goal**  Find \( p, q \in S \) such that \( d(p, q) \) is minimum
Closest Pair: 1-d case

**Input**  Given a set $S$ of $n$ points on a line

**Goal**  Find $p, q \in S$ such that $d(p, q)$ is minimum

**Algorithm**

1. Sort points based on coordinate
2. Compute the distance between successive points, keeping track of the closest pair.

Running time $O(n \log n)$

Can we do this in better running time? Can reduce Distinct Elements Problem (see lecture 1) to this problem in $O(n)$ time. Do you see how?
Generalizing 1-d case

Can we generalize 1-d algorithm to 2-d?
Sort according to $x$ or $y$-coordinate??
Generalizing 1-d case

Can we generalize 1-d algorithm to 2-d?
Sort according to $x$ or $y$-coordinate??
No easy generalization.
First Attempt

Divide and Conquer I

1. Partition into 4 quadrants of roughly equal size.
2. Find closest pair in each quadrant recursively.
3. Combine solutions.
First Attempt

Divide and Conquer I

1. Partition into 4 quadrants of roughly equal size. Not always!
2. Find closest pair in each quadrant recursively
3. Combine solutions
New Algorithm

Divide and Conquer II

1. Divide the set of points into two equal parts via vertical line
2. Find closest pair in each half recursively
3. Find closest pair with one point in each half
4. Return the best pair among the above 3 solutions
New Algorithm

Divide and Conquer II

1. Divide the set of points into two equal parts via vertical line
2. Find closest pair in each half recursively
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New Algorithm

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New Algorithm

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1. Divide the set of points into two equal parts via vertical line
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3. Find closest pair with one point in each half
4. Return the best pair among the above 3 solutions

Sort points based on $x$-coordinate and pick the median. Time $= O(n \log n)$

How to find closest pair with points in different halves?

$O(n^2)$ is trivial. Better?
New Algorithm

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Divide and Conquer II

1. Divide the set of points into two equal parts via vertical line
2. Find closest pair in each half recursively
3. Find closest pair with one point in each half
4. Return the best pair among the above 3 solutions

1. Sort points based on $x$-coordinate and pick the median. Time $= O(n \log n)$
2. How to find closest pair with points in different halves? $O(n^2)$ is trivial. Better?
1. Does it take $O(n^2)$ to combine solutions?

2. Let $\delta$ be the distance between closest pairs, where both points belong to the same half.
Combining Partial Solutions

1. Let $\delta$ be the distance between closest pairs, where both points belong to the same half.

2. Need to consider points within $\delta$ of dividing line.
Divide the band into square boxes of size $\delta/2$.

Lemma

Each box has at most one point.

Proof.

If not, then there are a pair of points (both belonging to one half) that are at most $\sqrt{2} \cdot \delta/2 < \delta$ apart!
Sparsity of Band XXX

Divide the band into square boxes of size $\delta/2$

**Lemma**

*Each box has at most one point*
Sparsity of Band XXX

Divide the band into square boxes of size $\frac{\delta}{2}$

Lemma

*Each box has at most one point*

Proof.

If not, then there are a pair of points (both belonging to one half) that are at most $\sqrt{2}\delta/2 < \delta$ apart!
Searching within the Band

Lemma

Suppose $a, b$ are both in the band $d(a, b) < \delta$ then $a, b$ have at most two rows of boxes between them.
Lemma
Suppose \( a, b \) are both in the band
\( d(a, b) < \delta \) then \( a, b \) have at most two rows
of boxes between them.

Proof.
Each row of boxes has height \( \delta/2 \). If more
than two rows then \( d(a, b) > 2 \cdot \delta/2! \)
Corollary

Order points according to their \( y \)-coordinate. If \( p, q \) are such that \( d(p, q) < \delta \) then \( p \) and \( q \) are within 11 positions in the sorted list.

Proof.

1. \( \leq 2 \) points between them if \( p \) and \( q \) in same row.
2. \( \leq 6 \) points between them if \( p \) and \( q \) in two consecutive rows.
3. \( \leq 10 \) points between if \( p \) and \( q \) one row apart.
4. \( \implies \) More than ten points between them in the sorted \( y \) order than \( p \) and \( q \) are more than two rows apart.
5. \( \implies \) \( d(p, q) > \delta \). A contradiction.
The Algorithm

**ClosestPair**($P$):

1. Split $P$ into equal-sized sets $P_1, P_2$ via vertical line $L$
2. $\delta_1 \leftarrow \text{ClosestPair}(P_1)$.
3. $\delta_2 \leftarrow \text{ClosestPair}(P_2)$.
4. $\delta = \min(\delta_1, \delta_2)$.
5. Delete points from $P$ further than $\delta$ from $L$.
6. Sort $P$ based on $y$-coordinate into an array $A$.
7. for $i = 1$ to $|A| - 1$ do
   
   for $j = i + 1$ to $\min\{i + 11, |A|\}$ do
   
   if ($\text{dist}(A[i], A[j]) < \delta$) update $\delta$ and closest pair.

---

1. Step 1 involves sorting and scanning. Takes $O(n \log n)$ time.
2. Step 5 takes $O(n)$ time.
3. Step 6 takes $O(n \log n)$ time.
The Algorithm

ClosestPair(\(P\)):
1. Split \(P\) into equal-sized sets \(P_1, P_2\) via vertical line \(L\)
2. \(\delta_1 \leftarrow \text{ClosestPair}(P_1)\).
3. \(\delta_2 \leftarrow \text{ClosestPair}(P_2)\).
4. \(\delta = \min(\delta_1, \delta_2)\)
5. Delete points from \(P\) further than \(\delta\) from \(L\)
6. Sort \(P\) based on \(y\)-coordinate into an array \(A\)
7. for \(i = 1\) to \(|A| - 1\) do
   for \(j = i + 1\) to \(\min\{i + 11, |A|\}\) do
     if (\(\text{dist}(A[i], A[j]) < \delta\)) update \(\delta\) and closest pair
The Algorithm

ClosestPair(P):
1. Split P into equal-sized sets P₁, P₂ via vertical line L
2. δ₁ ← ClosestPair(P₁).
3. δ₂ ← ClosestPair(P₂).
4. δ = \(\min(δ₁, δ₂)\)
5. Delete points from P further than δ from L
6. Sort P based on y-coordinate into an array A
7. for \(i = 1\) to |A| − 1 do
   for \(j = i + 1\) to \(\min\{i + 11, |A|\}\) do
     if \(\text{dist}(A[i], A[j]) < δ\) update δ and closest pair

Step 1, involves sorting and scanning. Takes \(O(n \log n)\) time.
The Algorithm

ClosestPair(\(P\)):
1. Split \(P\) into equal-sized sets \(P_1, P_2\) via vertical line \(L\)
2. \(\delta_1 \leftarrow \text{ClosestPair}(P_1)\).
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1. Step 1, involves sorting and scanning. Takes \(O(n \log n)\) time.
2. Step 5 takes \(O(n)\) time.
The Algorithm

**ClosestPair**(P):

1. Split P into equal-sized sets P₁, P₂ via vertical line L
2. \( \delta_1 \leftarrow \text{ClosestPair}(P_1) \).
3. \( \delta_2 \leftarrow \text{ClosestPair}(P_2) \).
4. \( \delta = \min(\delta_1, \delta_2) \).
5. Delete points from P further than \( \delta \) from L.
6. Sort P based on y-coordinate into an array A.
7. for \( i = 1 \) to \( |A| - 1 \) do
   for \( j = i + 1 \) to \( \min\{i + 11, |A|\} \) do
     if \( \text{dist}(A[i], A[j]) < \delta \) update \( \delta \) and closest pair

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1. Step 1, involves sorting and scanning. Takes \( O(n \log n) \) time.
2. Step 5 takes \( O(n) \) time.
The Algorithm

**ClosestPair**(\(P\)):

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1. Step 1, involves sorting and scanning. Takes \(O(n \log n)\) time.
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The Algorithm

ClosestPair(P):
1. Split P into equal-sized sets $P_1, P_2$ via vertical line L
2. $\delta_1 \leftarrow \text{ClosestPair}(P_1)$.
3. $\delta_2 \leftarrow \text{ClosestPair}(P_2)$.
4. $\delta = \min(\delta_1, \delta_2)$
5. Delete points from P further than $\delta$ from L
6. Sort P based on y-coordinate into an array A
7. for $i = 1$ to $|A| - 1$ do
   for $j = i + 1$ to $\min\{i + 11, |A|\}$ do
     if ($\text{dist}(A[i], A[j]) < \delta$) update $\delta$ and closest pair

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The Algorithm

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The Algorithm

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5. Delete points from \( P \) further than \( \delta \) from \( L \)
6. Sort \( P \) based on \( y \)-coordinate into an array \( A \)
7. \textbf{for} \( i = 1 \) to \( |A| - 1 \) \textbf{do}
   \quad \textbf{for} \( j = i + 1 \) to \( \min\{i + 11, |A|\} \) \textbf{do}
   \quad \textbf{if} \ (\text{dist}(A[i], A[j]) < \delta) \text{ update } \delta \text{ and closest pair}

\begin{itemize}
\item[1.] Step 1, involves sorting and scanning. Takes \( O(n \log n) \) time.
\item[2.] Step 5 takes \( O(n) \) time.
\item[3.] Step 6 takes \( O(n \log n) \) time
\item[4.] Step 7 takes \( O(n) \) time.
\end{itemize}
The running time of the algorithm is given by

\[ T(n) \leq 2T(n/2) + O(n \log n) \]
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Thus, \( T(n) = O(n \log^2 n) \).
Running Time

The running time of the algorithm is given by

$$T(n) \leq 2T(n/2) + O(n \log n)$$

Thus, $$T(n) = O(n \log^2 n)$$.  

Improved Algorithm

Avoid repeated sorting of points in band: two options

1. Sort all points by y-coordinate and store the list. In conquer step, use this to avoid sorting.

2. Each recursive call returns a list of points sorted by their y-coordinates. Merge in conquer step in linear time.

Analysis: $$T(n) \leq 2T(n/2) + O(n) = O(n \log n)$$
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. Sometimes one can look for certain type of recursive algorithms (reverse engineering) by understanding recurrences and their behavior.