Asymptotic Analysis

CSE 373
Data Structures & Algorithms
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Today’s Outline

• Announcements
  – Assignment #1 due Thurs, Oct 7 at 11:45pm

• Asymptotic Analysis

Exercise

```
bool ArrayFind(int array[], int n, int key)
// Insert your algorithm here
```

2 3 5 16 37 50 73 75 126

What algorithm would you choose to implement this code snippet?

Analyzing Code

Basic Java operations
Consecutive statements
Conditionals
Loops
Function calls
Recursive functions

Constant time
Sum of times
Larger branch plus test
Sum of iterations
Cost of function body
Solve recurrence relation

Analyze your code!

Linear Search Analysis

```
bool LinearArrayFind(int array[], int n, int key)
// Insert your algorithm here
```

Best Case:

Worst Case:

Binary Search Analysis

```
bool BinArrayFind(int array[], int low, int high, int key) {
    // The subarray is empty
    if( low > high ) return false;
    // Search this subarray recursively
    int mid = (high + low) / 2;
    if( key == array[mid] ) {
        return true;
    } else if( key < array[mid] ) 
        return BinArrayFind( array, low, mid-1, key );
    else {
        return BinArrayFind( array, mid+1, high, key );
    }
}
```

Best case:

Worst case:
Solving Recurrence Relations

1. Determine the recurrence relation. What is the base case(s)?

2. “Expand” the original relation to find an equivalent general expression in terms of the number of expansions.

3. Find a closed-form expression by setting the number of expansions to a value which reduces the problem to a base case.

Linear Search vs Binary Search

So … which algorithm is better?
What tradeoffs can you make?

Fast Computer vs Slow Computer

Fast Computer vs Smart Programmer
(round 1)

Asymptotic Analysis

- Asymptotic analysis looks at the order of the running time of the algorithm
  - A valuable tool when the input gets “large”
  - Ignores the effects of different machines or different implementations of the same algorithm
- Intuitively, to find the asymptotic runtime, throw away the constants and low-order terms
  - Linear search is $T(n) = 3n + 3 \in \Theta(n)$
  - Binary search is $T(n) = 5 \log_2 n + 7 \in \Theta(\log n)$

Remember: the fastest algorithm has the slowest growing function for its runtime.
Asymptotic Analysis

- Eliminate low order terms
  - $4n + 5 \Rightarrow -0.5 n \log n + 2n + 7 \Rightarrow -n^3 + 2n + 3n \Rightarrow$
- Eliminate coefficients
  - $4n \Rightarrow -0.5 n \log n \Rightarrow -n \log n \Rightarrow$

Order Notation: Intuition

Although not yet apparent, as $n$ gets “sufficiently large”, $f(n)$ will be “greater than or equal to” $g(n)$

Order Notation: Definition

- Upper bound: $T(n) = O(f(n))$  
  Exist constants $c$ and $n'$ such that $T(n) \leq c f(n)$ for all $n \geq n'$
- Lower bound: $T(n) = \Omega(g(n))$  
  Exist constants $c$ and $n'$ such that $T(n) \geq c g(n)$ for all $n \geq n'$
- Tight bound: $T(n) = \Theta(f(n))$  
  When both hold: $T(n) = O(f(n))$  
  $T(n) = \Omega(f(n))$

Order Notation: Example

- $f(n) = n^3 + 2n^2$
- $g(n) = 100n^2 + 1000$

Example: $g(n) = 100n^2 + 1000$ vs. $f(n) = n^3$

Is $g(n) \in O(f(n))$?

Pick: $n0 = 1000$, $c = 1$

Notation Notes

Note: Sometimes, you’ll see the notation:

$g(n) = \Theta(f(n))$.

This is equivalent to:

$g(n)$ is $O(f(n))$.

However: The notation

$O(f(n)) = g(n)$ is meaningless!

(in other words big-O “equality” is not symmetric)
Big-O: Common Names

- constant: $O(1)$
- logarithmic: $O(\log n)$ ($\log_k n, \log^2 n$ is $O(\log n)$)
- log-squared: $O(\log^2 n)$ ($\log^2 n = (\log n)(\log n)$)
- linear: $O(n)$
- log-linear: $O(n \log n)$
- quadratic: $O(n^2)$
- cubic: $O(n^3)$
- polynomial: $O(n^k)$ ($k$ is a constant)
- exponential: $O(c^n)$ ($c$ is a constant $> 1$)

Meet the Family

- $O(f(n))$ is the set of all functions asymptotically less than or equal to $f(n)$
- $o(f(n))$ is the set of all functions asymptotically strictly less than $f(n)$
- $\Omega(f(n))$ is the set of all functions asymptotically greater than or equal to $f(n)$
- $\omega(f(n))$ is the set of all functions asymptotically strictly greater than $f(n)$
- $\Theta(f(n))$ is the set of all functions asymptotically equal to $f(n)$

Meet the Family, Formally

- $g(n) \in O(f(n))$ iff
  - there exist $c$ and $n_0$ such that $g(n) \leq c f(n)$ for all $n \geq n_0$
  - $g(n) \in o(f(n))$ iff
    - there exists a $n_0$ such that $g(n) < c f(n)$ for all $c$ and $n \geq n_0$
- $g(n) \in \Omega(f(n))$ iff
  - equivalent to: $\lim_{n \to \infty} g(n)/f(n) = 0$
    - there exist $c > 0$ and $n_0$ such that $g(n) \geq c f(n)$ for all $n \geq n_0$
- $g(n) \in \omega(f(n))$ iff
  - equivalent to: $\lim_{n \to \infty} g(n)/f(n) = \infty$
    - there exists a $n_0$ such that $g(n) < c f(n)$ for all $c$ and $n \geq n_0$
- $g(n) \in \Theta(f(n))$ iff
  - $g(n) \in O(f(n))$ and $g(n) \in \Omega(f(n))$ (and $g(n) \in \omega(f(n))$)

Big-Omega et al. Intuitively

<table>
<thead>
<tr>
<th>Asymptotic Notation</th>
<th>Mathematics Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O$</td>
<td>$\leq$</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$\geq$</td>
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<tr>
<td>$\Theta$</td>
<td>$=$</td>
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<tr>
<td>$o$</td>
<td>$&lt;$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$&gt;$</td>
</tr>
</tbody>
</table>

Pros and Cons of Asymptotic Analysis

- bound flavor
  - upper bound ($O$, $o$)
  - lower bound ($\Omega$, $\omega$)
  - asymptotically tight ($\Theta$)
- analysis case
  - worst case (adversary)
  - average case
  - best case
  - “amortized”

Types of Analysis

Two orthogonal axes:

- bound flavor
  - upper bound ($O$, $o$)
  - lower bound ($\Omega$, $\omega$)
  - asymptotically tight ($\Theta$)
- analysis case
  - worst case (adversary)
  - average case
  - best case
  - “amortized”
Which Function Grows Faster?

\[ n^3 + 2n^2 \quad \text{vs.} \quad 100n^2 + 1000 \]

Which Function Grows Faster?

\[ n^{0.1} \quad \text{vs.} \quad \log n \]

Which Function Grows Faster?

\[ 5n^5 \quad \text{vs.} \quad n! \]
Nested Loops

```
for i = 1 to n do
  for j = 1 to n do
    sum = sum + 1

for i = 1 to n do
  for j = 1 to n do
    sum = sum + 1
```

16n^3 \log_8(10n^2) + 100n^2 = O(n^3 \log(n))

- Eliminate low order terms
- Eliminate constant coefficients

\[
16n^3 \log_8(10n^2) + 100n^2 = \frac{16n^3 \log_8(10n^2)}{n^3} + \frac{100n^2}{n^3}
\]

- Eliminate low order terms
- Eliminate constant coefficients

16n^3 \log_8(10n^2) + 100n^2 = O(n^3 \log(n))