Lecture 3: Program Analysis

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Topic: Problem of the Day
Problem of the Day

For each of the following pairs of functions \( f(n) \) and \( g(n) \), state whether \( f(n) = O(g(n)) \), \( f(n) = \Omega(g(n)) \), \( f(n) = \Theta(g(n)) \), or none of the above.

1. \( f(n) = n^2 + 3n + 4 \), \( g(n) = 6n + 7 \)
2. \( f(n) = n\sqrt{n} \), \( g(n) = n^2 - n \)
3. \( f(n) = 2^n - n^2 \), \( g(n) = n^4 + n^2 \)
Questions?
Topic: Multiplication and the Big Oh
Big Oh Multiplication by Constant

Multiplication by a constant does not change the asymptotics:

\[
O(c \cdot f(n)) \rightarrow O(f(n))
\]
\[
\Omega(c \cdot f(n)) \rightarrow \Omega(f(n))
\]
\[
\Theta(c \cdot f(n)) \rightarrow \Theta(f(n))
\]

The “old constant” \( C \) from the Big Oh becomes \( c \cdot C \).
But when both functions in a product are increasing, both are important:

\[ O(f(n)) \cdot O(g(n)) \rightarrow O(f(n) \cdot g(n)) \]
\[ \Omega(f(n)) \cdot \Omega(g(n)) \rightarrow \Omega(f(n) \cdot g(n)) \]
\[ \Theta(f(n)) \cdot \Theta(g(n)) \rightarrow \Theta(f(n) \cdot g(n)) \]

This is why the running time of two nested loops is \( O(n^2) \).
Questions?
Topic: Analyzing Algorithms: Selection and Insertion Sort
Grossly reasoning about the running time of an algorithm is usually easy given a precise-enough written description of the algorithm.

When you *really* understand an algorithm, this analysis can be done in your head. However, recognize there is always implicitly a written algorithm/program we are reasoning about.
Selection Sort

```c
void selection_sort(item_type s[], int n) {
    int i, j;    /* counters */
    int min;    /* index of minimum */

    for (i = 0; i < n; i++) {
        min = i;
        for (j = i + 1; j < n; j++) {
            if (s[j] < s[min]) {
                min = j;
            }
        }
        swap(&s[i], &s[min]);
    }
}
```
Worst Case Analysis

The outer loop goes around $n$ times.
The inner loop goes around at most $n$ times for each iteration of the outer loop.
Thus selection sort takes at most $n \times n \rightarrow O(n^2)$ time in the worst case.
In fact, it is $\Theta(n^2)$, because at least $n/2$ times it scans through at least $n/2$ elements, for a total of at least $n^2/4$ steps.
More Careful Analysis

An exact count of the number of times the if statement is executed is given by:

\[ S(n) = \sum_{i=0}^{n-1} \sum_{j=i+1}^{n-1} 1 = \sum_{i=0}^{n-1} (n - i + 1) = \sum_{i=0}^{n-1} i \]

\[ S(n) = (n - 1) + (n - 2) + (n - 3) + \ldots + 2 + 1 = n(n + 1)/2 \]

Thus the worst case running time is \( \Theta(n^2) \).
Insertion Sort

```c
void insertion_sort(item_type s[], int n) {
    int i, j; /* counters */
    for (i = 1; i < n; i++) {
        j = i;
        while ((j > 0) && (s[j] < s[j - 1])) {
            swap(&s[j], &s[j - 1]);
            j = j-1;
        }
    }
}
```

This involves a while loop, so the analysis is less mechanical. But $n$ calls to an inner loop which takes at most $n$ steps on each call is $O(n^2)$. The reverse-sorted permutation proves that the worst-case complexity is $\Theta(n^2)$: (10, 9, 8, 7, 6, 5, 4, 3, 2, 1)
Questions?
Topic: Asymptotic Dominance
Solar Sails vs. Rockets

The bad-ass rocket hits a high speed before it runs out of fuel, then coasts at constant speed $v_r$.
The solar sail slowly accelerates from the force of radiation/solar wind hitting it, but its speed of $v_s = at$ must eventually exceed the bad-ass rocket.
This is asymptotic dominance in action.
### Asymptotic Dominance in Action

<table>
<thead>
<tr>
<th>$n$</th>
<th>$f(n)$</th>
<th>$\lg n$</th>
<th>$n$</th>
<th>$n \lg n$</th>
<th>$n^2$</th>
<th>$2^n$</th>
<th>$n!$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td>0.003 μs</td>
<td>0.01 μs</td>
<td>0.033 μs</td>
<td>0.1 μs</td>
<td>1 μs</td>
<td>3.63 ms</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.004 μs</td>
<td>0.02 μs</td>
<td>0.086 μs</td>
<td>0.4 μs</td>
<td>1 ms</td>
<td>77.1 years</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.005 μs</td>
<td>0.03 μs</td>
<td>0.147 μs</td>
<td>0.9 μs</td>
<td>1 sec</td>
<td>8.4 × 10^{15} yrs</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>0.005 μs</td>
<td>0.04 μs</td>
<td>0.213 μs</td>
<td>1.6 μs</td>
<td>18.3 min</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>0.006 μs</td>
<td>0.05 μs</td>
<td>0.282 μs</td>
<td>2.5 μs</td>
<td>13 days</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>0.007 μs</td>
<td>0.1 μs</td>
<td>0.644 μs</td>
<td>10 μs</td>
<td>100 ms</td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td></td>
<td>0.010 μs</td>
<td>1.00 μs</td>
<td>9.966 μs</td>
<td>100 ms</td>
<td>16.7 min</td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td></td>
<td>0.013 μs</td>
<td>10 μs</td>
<td>130 μs</td>
<td>10 sec</td>
<td>115.7 days</td>
<td></td>
</tr>
<tr>
<td>100,000</td>
<td></td>
<td>0.017 μs</td>
<td>0.10 ms</td>
<td>1.67 ms</td>
<td>16 sec</td>
<td>31.7 years</td>
<td></td>
</tr>
<tr>
<td>1,000,000</td>
<td></td>
<td>0.020 μs</td>
<td>1 ms</td>
<td>19.93 ms</td>
<td>16.7 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10,000,000</td>
<td></td>
<td>0.023 μs</td>
<td>0.01 sec</td>
<td>0.23 sec</td>
<td>1.16 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,000,000</td>
<td></td>
<td>0.027 μs</td>
<td>0.10 sec</td>
<td>2.66 sec</td>
<td>115.7 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,000,000,000</td>
<td></td>
<td>0.030 μs</td>
<td>1 sec</td>
<td>29.90 sec</td>
<td>31.7 years</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Implications of Dominance

- Exponential algorithms get hopeless fast.
- Quadratic algorithms get hopeless at or before 1,000,000.
- $O(n \log n)$ is possible to about one billion.
- $O(\log n)$ never sweats.
Questions?
Topic: Determining Asymptotic Dominance
Testing Dominance

\( f(n) \) dominates \( g(n) \) if \( \lim_{n \to \infty} \frac{g(n)}{f(n)} = 0 \), which is the same as saying \( g(n) = o(f(n)) \). Note the little-oh – it means “grows strictly slower than”.
Properties of Dominance

- $n^a$ dominates $n^b$ if $a > b$ since
  \[
  \lim_{n \to \infty} \frac{n^b}{n^a} = n^{b-a} \to 0
  \]

- $n^a + o(n^a)$ doesn’t dominate $n^a$ since
  \[
  \lim_{n \to \infty} \frac{n^a}{n^a + o(n^a)} \to 1
  \]
**Dominance Rankings**

You must come to accept the dominance ranking of the basic functions:

\[ n! \gg 2^n \gg n^3 \gg n^2 \gg n \log n \gg n \gg \log n \gg 1 \]
Advanced Dominance Rankings

Additional functions arise in more sophisticated analysis than we will do in this course:

\[ n! \gg c^n \gg n^3 \gg n^2 \gg n^{1+\epsilon} \gg n \log n \gg n \gg \sqrt{n} \gg \log^2 n \gg \log n \gg \log n/\log\log n \gg \log\log n \gg \alpha(n) \gg 1 \]
Questions?
Topic: Logarithms
Logarithms

It is important to understand deep in your bones what logarithms are and where they come from. A logarithm is simply an inverse exponential function. Saying $b^x = y$ is equivalent to saying that $x = \log_b y$. Logarithms reflect how many times we can double something until we get to $n$, or halve something until we get to 1.
Binary Search

In binary search we throw away half the possible number of keys after each comparison. Thus twenty comparisons suffice to find any name in the million-name Manhattan phone book! How many times can we halve $n$ before getting to 1? Answer: $\lceil \log n \rceil$. 
How tall a binary tree do we need until we have \( n \) leaves? The number of potential leaves doubles with each level. How many times can we double 1 until we get to \( n \)?

Answer: \( \left\lceil \lg n \right\rceil \).
Logarithms and Bits

How many bits do you need to represent the numbers from 0 to $2^i - 1$?
Each bit you add doubles the possible number of bit patterns, so the number of bits equals $\lg(2^i) = i$. 
Logarithms and Multiplication

Recall that

$$\log_a(xy) = \log_a(x) + \log_a(y)$$

This is how people used to multiply before calculators, and remains useful for analysis.

What if $x = a$?
The Base is not Asymptotically Important

Recall the definition, \( c^{\log_c x} = x \) and that

\[
\log_b a = \frac{\log_c a}{\log_c b}
\]

Thus \( \log_2 n = (1/\log_{100} 2) \times \log_{100} n \). Since \( 1/\log_{100} 2 = 6.643 \) is just a constant, it does not matter in the Big Oh.
Federal Sentencing Guidelines

2F1.1. Fraud and Deceit; Forgery; Offenses Involving Altered or Counterfeit Instruments other than Counterfeit Bearer Obligations of the United States.
(a) Base offense Level: 6
(b) Specific offense Characteristics

(1) If the loss exceeded $2,000, increase the offense level as follows:

<table>
<thead>
<tr>
<th>Loss (Apply the Greatest)</th>
<th>Increase in Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) $2,000 or less</td>
<td>no increase</td>
</tr>
<tr>
<td>(B) More than $2,000</td>
<td>add 1</td>
</tr>
<tr>
<td>(C) More than $5,000</td>
<td>add 2</td>
</tr>
<tr>
<td>(D) More than $10,000</td>
<td>add 3</td>
</tr>
<tr>
<td>(E) More than $20,000</td>
<td>add 4</td>
</tr>
<tr>
<td>(F) More than $40,000</td>
<td>add 5</td>
</tr>
<tr>
<td>(G) More than $70,000</td>
<td>add 6</td>
</tr>
<tr>
<td>(H) More than $120,000</td>
<td>add 7</td>
</tr>
<tr>
<td>(I) More than $200,000</td>
<td>add 8</td>
</tr>
<tr>
<td>(J) More than $350,000</td>
<td>add 9</td>
</tr>
<tr>
<td>(K) More than $500,000</td>
<td>add 10</td>
</tr>
<tr>
<td>(L) More than $800,000</td>
<td>add 11</td>
</tr>
<tr>
<td>(M) More than $1,500,000</td>
<td>add 12</td>
</tr>
<tr>
<td>(N) More than $2,500,000</td>
<td>add 13</td>
</tr>
<tr>
<td>(O) More than $5,000,000</td>
<td>add 14</td>
</tr>
<tr>
<td>(P) More than $10,000,000</td>
<td>add 15</td>
</tr>
<tr>
<td>(Q) More than $20,000,000</td>
<td>add 16</td>
</tr>
<tr>
<td>(R) More than $40,000,000</td>
<td>add 17</td>
</tr>
<tr>
<td>(Q) More than $80,000,000</td>
<td>add 18</td>
</tr>
</tbody>
</table>
Make the Crime Worth the Time

The increase in punishment level grows logarithmically in the amount of money stolen.
Thus it pays to commit one big crime rather than many small crimes totalling the same amount.
Questions?