Lecture 3: Program Analysis

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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. $f(n) = 2^n - n^2$, $g(n) = n^4 + n^2$
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 \(O(n^2)\).
Reasoning About Efficiency

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

```
selection_sort(int s[], int n)
{
    int i, j;
    int min;

    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

```
insertion_sort(item 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, instead of just for loops, 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 for insertion sort is $\Theta(n^2)$.

$$(10, 9, 8, 7, 6, 5, 4, 3, 2, 1)$$
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 ( \mu s )</td>
<td>0.01 ( \mu s )</td>
<td>0.033 ( \mu s )</td>
<td>0.1 ( \mu s )</td>
<td>1 ( \mu s )</td>
<td>3.63 ms</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.004 ( \mu s )</td>
<td>0.02 ( \mu s )</td>
<td>0.086 ( \mu s )</td>
<td>0.4 ( \mu s )</td>
<td>1 ( ms )</td>
<td>77.1 years</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.005 ( \mu s )</td>
<td>0.03 ( \mu s )</td>
<td>0.147 ( \mu s )</td>
<td>0.9 ( \mu s )</td>
<td>1 ( sec )</td>
<td>8.4 ( \times 10^{15} ) yrs</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>0.005 ( \mu s )</td>
<td>0.04 ( \mu s )</td>
<td>0.213 ( \mu s )</td>
<td>1.6 ( \mu s )</td>
<td>18.3 min</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>0.006 ( \mu s )</td>
<td>0.05 ( \mu s )</td>
<td>0.282 ( \mu s )</td>
<td>2.5 ( \mu s )</td>
<td>13 days</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>0.007 ( \mu s )</td>
<td>0.1 ( \mu s )</td>
<td>0.644 ( \mu s )</td>
<td>10 ( \mu s )</td>
<td>4 ( \times 10^{13} ) yrs</td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td></td>
<td>0.010 ( \mu s )</td>
<td>1.00 ( \mu s )</td>
<td>9.966 ( \mu s )</td>
<td>100 ( \mu s )</td>
<td>1 ms</td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td></td>
<td>0.013 ( \mu s )</td>
<td>10 ( \mu s )</td>
<td>130 ( \mu s )</td>
<td>10 sec</td>
<td>100 ms</td>
<td></td>
</tr>
<tr>
<td>100,000</td>
<td></td>
<td>0.017 ( \mu s )</td>
<td>1.0 ms</td>
<td>1.67 ms</td>
<td>16 sec</td>
<td>10 sec</td>
<td></td>
</tr>
<tr>
<td>1,000,000</td>
<td></td>
<td>0.020 ( \mu s )</td>
<td>1 ms</td>
<td>19.93 ms</td>
<td>16.7 min</td>
<td>16.7 min</td>
<td></td>
</tr>
<tr>
<td>10,000,000</td>
<td></td>
<td>0.023 ( \mu s )</td>
<td>0.01 sec</td>
<td>0.23 sec</td>
<td>1.16 days</td>
<td>1.16 days</td>
<td></td>
</tr>
<tr>
<td>100,000,000</td>
<td></td>
<td>0.027 ( \mu s )</td>
<td>0.10 sec</td>
<td>2.66 sec</td>
<td>115.7 days</td>
<td>115.7 days</td>
<td></td>
</tr>
<tr>
<td>1,000,000,000</td>
<td></td>
<td>0.030 ( \mu s )</td>
<td>1 sec</td>
<td>29.90 sec</td>
<td>31.7 years</td>
<td>31.7 years</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.
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:

\[ n! \gg c^n \gg n^3 \gg n^2 \gg n^{1+\epsilon} \gg n \log n \gg n \gg \sqrt{n} \gg \log^2 n \gg \log n \gg \log n / \log \log n \gg \log \log n \gg \alpha(n) \gg 1 \]
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 time can we halve $n$ before getting to $1$?

Answer: $\lceil \lg n \rceil$. 
Logarithms and Trees

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: $\lceil \lg n \rceil$. 
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 \( \log_2 n = \left( \frac{1}{\log_{100} 2} \right) \times \log_{100} n \). Since \( \frac{1}{\log_{100} 2} = 6.643 \) is just a constant, it does not matter in the Big Oh.
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 \textit{logarithmically} in the amount of money stolen. Thus it pays to commit one big crime rather than many small crimes totalling the same amount.