CS 162 Notes (Winter 2017)

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Chapter 1

Asymptotic Analysis

1.1 Big-Oh Notation

1.1.1 Definition

We have that a function $f \in O(g(n))$ if and only if there exists constants c and n_0 such that $f(n) \leq cg(n)$ for all $n \geq n_0$.

We have that a function $f \in \Omega(g(n))$ if and only if there exists constants c and n_0 such that $f(n) \leq cg(n)$ for all $n \leq n_0$.

We have that a function $f \in \Theta(g(n))$ if and only if $f \in O(g(n))$ and $f \in \Omega(g(n))$.

This notation can be used to analyze the best-case, average-case, and worse-case efficiency of an algorithm, but this class typically concerns the worst-case efficiency of an algorithm.

Note that efficiency can be a measure of time, space, or even power complexity.

1.1.2 Assumption: Constant Operations (Approximations)

- Arithmetic (fixed width)
- Assignment
- Access any array element

1.1.3 Non-Constant Operations

Control Flow	Time
Consecutive statements	Sum of time of each statement
Conditional	Time of test + time of the slower branch
Loop	Number of iterations * time of body
Function call	Time of function body
Recursion	Solve recurrence relation

1.2 Reducing Big-O Expressions

1.2.1 What to Eliminate

- Eliminate low-order terms
- Eliminate coefficients

1.2.2 Examples

- $4n + 5 \in O(n)$
- $\frac{1}{2}n \log n + 2n + 7 \in O(n \log n)$
- $n^3 + 2^n + 3n \in O(2^n)$
- $n \log(10n^2) + 2n \log n \in O(n \log n)$
  - Note that $n \log(10n^2) = 2n \log(10n)$

1.3 Linear Search

1.3.1 Code

```
int find(int[] arr, int arr_length, int k) {
    for (int i = 0; i < arr_length; ++i) {
        if (arr[i] == k) {
            return 1;
        }
    }
    return 0;
}
```

1.3.2 Analysis

- Best case: approximately six steps
  - $O(1)$
- Worst case: $6 *$ arr_length steps
  - $n =$ arr_length, so $O(n)$

1.4 Binary Search

1.4.1 Code

```
int find(int[] arr, int k, int lo, int hi) {
    return help(arr, k, 0, arr_length);
}

int find(int[] arr, int arr_length, int k) {
    int mid = (hi + lo) / 2;
    if (lo == hi) {
        return 0;
    }
```

```
    if (arr[mid] == k) {
        return 1;
    }
    if (arr[mid] < k) {
        return help(arr, k, mid + 1, k);
    } else {
        return help(arr, k, lo, mid);
    }
}
```

1.4.2 Analysis

Let $T(n)$ be the efficiency of `find`. Then, because each split takes approximately ten operations, we have that:

$$\begin{aligned}
T(n) &= 10 + T\left(\frac{n}{2}\right) \\
&= 10 + \left(10 + T\left(\frac{n}{4}\right)\right) \\
&= 10 + \left(10 + \left(10 + T\left(\frac{n}{8}\right)\right)\right) \\
&= 10k + T\left(\frac{n}{2^k}\right).
\end{aligned}$$

To solve this, there are a couple methods.

1.5 Methods of Asymptotic Analysis

1.5.1 Method 1

Let $\frac{n}{2^k} = 1$, so then $k = \log n$. Then

$$\begin{aligned}
T(n) &= 10 \log n + T\left(\frac{n}{2^{\log n}}\right) \\
&= 10 \log n + T(1) \\
&= 10 \log n + 10 \\
&\in O(\log n).
\end{aligned}$$

However, this method actually gives you a big-theta approximation for T; in other words, not only is $T \in O(\log n)$, we also have that $T \in \Theta(\log n)$.

1.5.2 Method 2 (Substitution Method)

Guess $O(?)$, then check. For example (in this case), guess $\log n$ because we have something like $\frac{n}{2^n}$ in the formula. Then:

$$\begin{aligned}
T(n) &= 10 + T(n/2) \\
&= 10 + \log(n/2)
\end{aligned}$$

Because we have guessed that $T \in O(\log n)$, we have that $T(n) \leq c \log n$ for all $n \geq n_0$, for some constants c, n_0.

$$\begin{aligned} T(n) &\leq c \log n \\ 10 + \log(n/2) &\leq c \log n \\ 10 + \log(n) - \log(2) &\leq c \log n \\ \frac{10 + \log(n) - \log(2)}{\log n} &\leq c \\ \frac{10}{\log n} + 1 - \frac{\log(2)}{\log n} &\leq c \\ \frac{10}{\log n} + 1 - \frac{1}{\log n} &\leq c \end{aligned}$$

Now take $n_0 = 2$, so $n \geq 2$ and thus $\log n \geq 1$ (log is base two). We then have:

$$\begin{aligned} c &\geq \frac{10}{1} + 1 - \frac{1}{1} \\ c &\geq 10 \end{aligned}$$

Therefore, $T \in O(\log n)$ because with $c = 10$ and $n_0 = 2$, we have that $T(n) \leq c \log n$ for all $n \geq n_0$.

Note that the substituion method is more general than *Method 1*, but it does *not* give you a big-theta approximation (unlike *Method 1*).

1.5.3 Examples

Example 1: $f(n) = 45n \log n + 2n^2 + 65$. We will use the substitution method, with a guess of $f \in O(n^2)$.

$$\begin{aligned} cn^2 &\geq 45n \log n + 2n^2 + 65 \\ c &\geq \frac{45n \log n + 2n^2 + 65}{n^2} \\ c &\geq \frac{45 \log n}{n} + 2 + \frac{65}{n^2} \end{aligned}$$

TODO

1.6 The Towers of Hanoi

1.6.1 Gameplay

The goal of the Towers of Hanoi is to move all disks to goal peg, with the following rules:

- You can only move one disk at a time
- You can only move the top-most disk in a pile
- You cannot put a larger disk on top of a smaller one

1.6.2 Algorithmic Solution

```
if n = 1:                                => T(1)
    move to goal (base case)                  = 1
else:                                    => T(n)
    move top n-1 disks to temporary peg       = T(n - 1)
    move bottom disk to goal                  + T(1)
    move the n-1 disks to goal                + T(n - 1)
```

Thus, $T(n) = T(n-1) + T(1) + T(n-1)$, with $T(1) = 1$. So:

$$\begin{aligned} T(n) &= 2T(n-1) + 1 \\ &= 2(2T(n-2) + 1) + 1 \\ &= 4T(n-2) + 3 \\ &= 4(2T(n-3) + 1) + 3 \\ &= 8T(n-3) + 7. \end{aligned}$$

By inspection, we have:

$$T(n) = 2^{n-1}T(1) + (2^{n-1} - 1),$$

but $T(1) = 1$, so we have:

$$\begin{aligned} T(n) = 2^{n-1} + 2^{n-1} - 1, & \\ &= 2^n - 1 \\ &\in \Theta(2^n). \end{aligned}$$