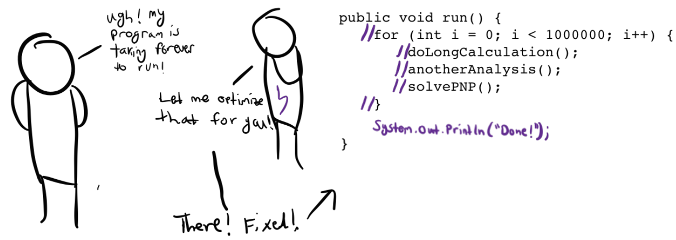
CSE 332

Data Abstractions

Algorithm Analysis 1



Outline

Comparing Programs

In 143, we asked:

What does it mean to have an "efficient program"?

```
System.out.println("hello");
```

vs.

```
System.out.print("h");
System.out.print("e");
System.out.print("l");
System.out.print("l");
System.out.println("o");
```

OUTPUT
```
>> left average run time is 1000 ns.
>> right average run time is 5000 ns.
```

We're measuring in NANOSECONDS!

Both of these run **very very** quickly. The first is definitely better style, but it's not "more efficient."

Comparing Programs: Timing

hasDuplicate
Given a **sorted int array**, determine if the array has a duplicate.

Algorithm 1
For each **pair of elements**, check if they're the same.

Algorithm 2
For each **element**, check if it's equal to the one after it.

Why Not Time Programs?
Timing programs is prone to error (not **reliable** or **portable**):
- Hardware: processor(s), memory, etc.
- OS, Java version, libraries, drivers
- Other programs running
- Implementation dependent
- Can we even time an algorithm?

Comparing Programs: # Of Steps

hasDuplicate
Given a **sorted int array**, determine if the array has a duplicate.

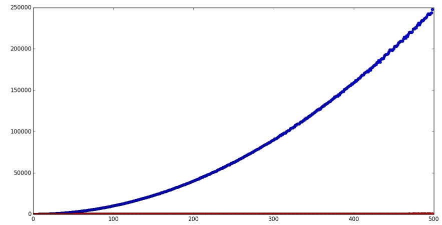
Example
```
public int stepsHasDuplicate1(int[] array) {
   int steps = 0;
   for (int i=0; i < array.length; i++) {
      for (int j=0; j < array.length; j++) {
         steps++; // The if statement is a step
         if (i != j && array[i] == array[j]) {
            return steps;
         }
      }
   }
   return steps;
}
```

OUTPUT
```
>> hasDuplicate1 average number of steps is 9758172 steps.
>> hasDuplicate2 average number of steps is 170 steps.
```

Why Not Count Steps in Programs?
- Can we even count steps for an algorithm?
- We must do this via **testing**; so, we may miss worst-case input!
- We must do this via **testing**; so, we may miss best-case input!

Comparing Programs: Plotting

Instead, let's try running on arrays of size 1, 2, 3, . . . , 1000000, and plot:



Why Not Plot Steps in Programs?

- Can we even count steps for an algorithm?
- We must do this via **testing**; so, we may miss worst-case input!
- We must do this via **testing**; so, we may miss best-case input!

Comparing ~~Programs~~ Algorithms: Our Requirements

We want to compare **algorithms**, not programs. In general, there are many answers (clarity, security, etc.). Performance (space, time, etc.) are generally among the most important.

- Only consider large inputs (any algorithm will work on 10)
- Answer will be independent of CPU speed, programming language, coding tricks, etc.
- Answer is general and rigorous, complementary to "coding it up and counting steps on some test cases"
- Can do analysis before coding!

Comparing Code: Analytically

Basic Operations take "some amount of" Constant Time

- Arithmetic (fixed-width)
- Variable Assignment
- Access one Java field or array index
- etc.

(This is an approximation of reality: a very useful "lie".)

Complex Operations

Consecutive Statements. Sum of time of each statement
Conditionals. Time of condition + `max(ifBranch, elseBranch)`
Loops. Number of iterations ∗ Time for Loop Body
Function Calls. Time of function's body
Recursive Function Calls. Solve Recurrence

Analyzing `hasDuplicate`

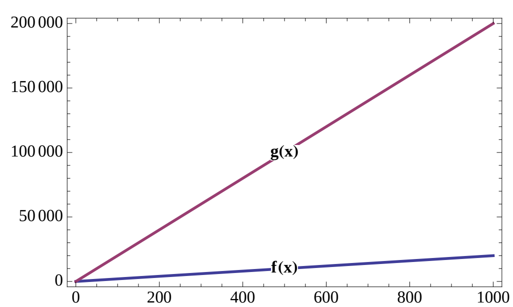

```
public boolean hasDuplicate1(int[] array) {
   for (int i=0; i < array.length; i++) { // 1
      for (int j=0; j < array.length; j++) {
         if (i != j && array[i] == array[j]) { // 1
            return true;            // 1
         }
      }
   }
   return false;                    // 1
}
```

$\}\,2$ $\}\,2N$ $\}\,(2N+1)N$

```
public boolean hasDuplicate2(int[] array) {
   for (int i=0; i < array.length - 1; i++) { // 1
      if (array[i] == array[i+1]) { // 1
         return true;            // 1
      }
   }
   return false;                 // 1
}
```

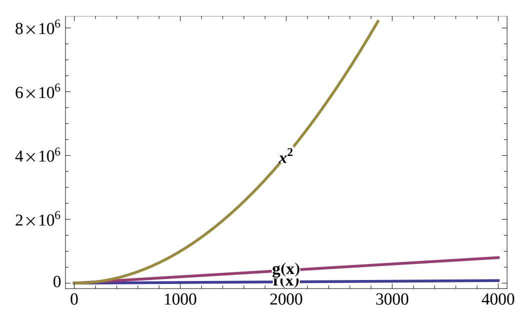
$\}\,2$ $\}\,2N$ $\}\,2N+1$

Investigating with Pictures



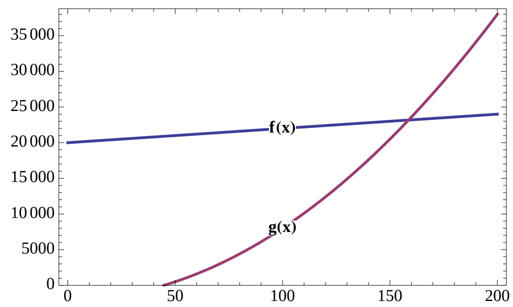
Should we consider these "the same"?

Investigating with Pictures



Probably a good idea, since they seem to be growing at the same rate. For reference, the function that dwarfs them both is x^2.

Investigating with Pictures 2



Here's two functions, $f(x)$ and $g(x)$. Ultimately, $g(x)$ will grow much faster than $f(x)$, but at the beginning, it is smaller.

Asymptotics

We'd like to be able to compare two functions. Intuitively, we want an operation like "$\leq$" (e.g. $4 \leq 5$), but for functions.

If we have f and $4f$, we should consider them the same:

$f \leq g$ when...

$f \leq cg$ where c is a constant and $c \neq 0$.

We also care about **all values of the function** that are **big enough**:

$f \leq g$ when...

For all n "large enough", $f(n) \leq cg(n)$, where $c \neq 0$
For some $n_0 \geq 0$, for all $n \geq n_0$, $f(n) \leq cg(n)$, where $c \neq 0$
For some $c \neq 0$, for some $n_0 \geq 0$, for all $n \geq n_0$, $f(n) \leq cg(n)$

Definition (Big-Oh)

We say a function $f : A \to B$ **is dominated by** a function $g : A \to B$ when:

$$\exists(c, n_0 > 0).\ \forall(n \geq n_0).\ f(n) \leq cg(n)$$

Formally, we write this as $f \in \mathcal{O}(g)$.

Big-Oh Examples

True or False?

(1) $4 + 3n \in \mathcal{O}(n)$ True $(n = n)$
(2) $4 + 3n = \mathcal{O}(1)$ False: $(n >> 1)$
(3) $4 + 3n$ is $\mathcal{O}(n^2)$ True: $(n \leq n^2)$
(4) $n + 2\log n \in \mathcal{O}(\log n)$ False: $(n >> \log n)$
(5) $\log n \in \mathcal{O}(n + 2\log n)$ True: $(\log n \leq n + 2\log n)$

Big-Oh Gotchas

- $\mathcal{O}(f)$ is a **set**! This means we should treat it as such.
- If we know $f(n) \in \mathcal{O}(n)$, then it is also the case that $f(n) \in \mathcal{O}(n^2)$, and $f(n) \in \mathcal{O}(n^3)$, etc.
- Remember that small cases, really don't matter. As long as it's **eventually** an upper bound, it fits the definition.

Okay, but we haven't actually shown anything. Let's **prove** (1) and (2).

Big-Oh Proofs

Definition (Big-Oh)

We say a function $f : A \to B$ **is dominated by** a function $g : A \to B$ when:

$$\exists(c, n_0 > 0).\ \forall(n \geq n_0).\ f(n) \leq cg(n)$$

Formally, we write this as $f \in \mathcal{O}(g)$.

We want to prove $4 + 3n \in \mathcal{O}(n)$. That is, we want to prove:

$$\exists(c, n_0 > 0).\ \forall(n \geq n_0).\ 4 + 3n \leq cn$$

Proof Strategy

- Choose a c, n_0 that work.
- Prove that they work for all $n \geq n_0$.

Proof

Choose $c = 5$ and $n_0 = 5$. Then, note that $4 + 3n \leq 4n \leq 5n$, because $n \geq 5$. It follows that $4 + 3n \in \mathcal{O}(n)$.

Big-Oh Proofs 2

Definition (Big-Oh)

We say a function $f : A \to B$ **is dominated by** a function $g : A \to B$ when:

$$\exists(c, n_0 > 0).\ \forall(n \geq n_0).\ f(n) \leq cg(n)$$

Formally, we write this as $f \in \mathcal{O}(g)$.

We want to prove $4 + 3n + 4n^2 \in \mathcal{O}(n^3)$.

Scratch Work

We want to choose a c and n_0 such that $4 + 3n + 4n^2 \leq cn^3$. So, manipulate the equation:

$$4 + 3n + 4n^2 \leq 4n^3 + 3n^3 + 4n^3 = 11n^3$$

For this to work, we need $4 \leq 4n^3$ and $3n \leq 3n^3$. $n \geq 1$ satisfies this.

Proof

Choose $c = 11$ and $n_0 = 1$. Then, note that $4 + 3n + 4n^2 \leq 4n^3 + 3n^3 + 4n^3 = 11n^3$, because $n \geq 1$. It follows that $4 + 3n + 4n^2 \in \mathcal{O}(n^3)$.

More Asymptotics

Definition (Big-Oh)

We say a function $f : A \to B$ **is dominated by** a function $g : A \to B$ when:

$$\exists(c, n_0 > 0).\ \forall(n \geq n_0).\ f(n) \leq cg(n)$$

Formally, we write this as $f \in \mathcal{O}(g)$.

Definition (Big-Omega)

We say a function $f : A \to B$ **dominates** a function $g : A \to B$ when:

$$\exists(c, n_0 > 0).\ \forall(n \geq n_0).\ f(n) \geq cg(n)$$

Formally we write this as $f \in \Omega(g)$.

Definition (Big-Theta)

We say a function $f : A \to B$ **grows at the same rate as** a function $g : A \to B$ when: $f \in \mathcal{O}(g)$ and $f \in \Omega(g)$
Formally we write this as $f \in \Theta(g)$.

Important: You need not use the same c value for $\mathcal{O}$ and Ω to prove Θ.

Theta

True or False?

(1) $4+3n \in \Theta(n)$ True

(2) $4+3n$ is $\Theta(n^2)$ False

If you want to say "f is a tight bound for g", **do not use** $\mathcal{O}$–use Θ.

It's the Worst Case!

Remember, we're analyzing the **worst** case **time**! What else can we analyze?

- Space?
- Average Case?
- Best Case?
- Time **over multiple operations**?

Final Note

Which is Better?

$$n^{1/10} \text{ or } \log n$$

- $\log n$ grows more slowly (Big-Oh)
- ... But the cross-over point is around 5×10^{17}

Today's Takeaways!

- There are many ways to compare algorithms
- Understand formal Big-Oh, Big-Omega, Big-Theta
- Be able to prove any of these