

Data Structures and Algorithms

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Algorithm Analysis

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02-0: Algorithm Analysis

When is algorithm A better than algorithm B?

02-1: Algorithm Analysis

When is algorithm A better than algorithm B?

- Algorithm A runs faster

02-2: Algorithm Analysis

When is algorithm A better than algorithm B?

- Algorithm A runs faster
- Algorithm A requires less space to run

02-3: Algorithm Analysis

When is algorithm A better than algorithm B?

- Algorithm A runs faster
- Algorithm A requires less space to run

Space / Time Trade-off

- Can often create an algorithm that runs faster, by using more space

For now, we will concentrate on time efficiency

02-4: Best Case vs. Worst Case

How long does the following function take to run:

```
boolean find(int A[], int element) {  
    for (i=0; i<A.length; i++) {  
        if (A[i] == elem)  
            return true;  
    }  
    return false;  
}
```

02-5: Best Case vs. Worst Case

How long does the following function take to run:

```
boolean find(int A[], int element) {  
    for (i=0; i<A.length; i++) {  
        if (A[i] == elem)  
            return true;  
    }  
    return false;  
}
```

It depends on if – and where – the element is in the list

02-6: Best Case vs. Worst Case

- Best Case – What is the fastest that the algorithm can run
- Worst Case – What is the slowest that the algorithm can run
- Average Case – How long, on average, does the algorithm take to run

Worst Case performance is almost always important.
Usually, Best Case performance is unimportant (why?)
Usually, Average Case = Worst Case (but not always!)

02-7: Measuring Time Efficiency

How long does an algorithm take to run?

02-8: Measuring Time Efficiency

How long does an algorithm take to run?

- Implement on a computer, time using a stopwatch.

02-9: Measuring Time Efficiency

How long does an algorithm take to run?

- Implement on a computer, time using a stopwatch.
Problems:
 - Not just testing algorithm – testing implementation of algorithm
 - Implementation details (cache performance, other programs running in the background, etc) can affect results
 - Hard to compare algorithms that are not tested under *exactly the same conditions*

02-10: Measuring Time Efficiency

How long does an algorithm take to run?

- Implement on a computer, time using a stopwatch.
Problems:
 - Not just testing algorithm – testing implementation of algorithm
 - Implementation details (cache performance, other programs running in the background, etc) can affect results
 - Hard to compare algorithms that are not tested under *exactly the same conditions*
- Better Method: Build a mathematical model of the running time, use model to compare algorithms

02-11: Competing Algorithms

- Linear Search

```
for (i=low; i <= high; i++)  
    if (A[i] == elem) return true;  
return false;
```

- Binary Search

```
int BinarySearch(int low, int high, elem) {  
    if (low > high) return false;  
    mid = (high + low) / 2;  
    if (A[mid] == elem) return true;  
    if (A[mid] < elem)  
        return BinarySearch(mid+1, high, elem);  
    else  
        return BinarySearch(low, mid-1, elem);  
}
```

02-12: Linear vs Binary

- Linear Search

```
for (i=low; i <= high; i++)  
    if (A[i] == elem) return true;  
return false;
```

Time Required, for a problem of size n (worst case):

02-13: Linear vs Binary

- Linear Search

```
for (i=low; i <= high; i++)  
    if (A[i] == elem) return true;  
return false;
```

Time Required, for a problem of size n (worst case):

$c_1 * n$ for some constant c_1

02-14: Linear vs Binary

- Binary Search

```
int BinarySearch(int low, int high, elem) {
    if (low > high) return false;
    mid = (high + low) / 2;
    if (A[mid] == elem) return true;
    if (A[mid] < elem)
        return BinarySearch(mid+1, high, elem);
    else
        return BinarySearch(low, mid-1, elem);
}
```

Time Required, for a problem of size n (worst case):

02-15: Linear vs Binary

- Binary Search

```
int BinarySearch(int low, int high, elem) {
    if (low > high) return false;
    mid = (high + low) / 2;
    if (A[mid] == elem) return true;
    if (A[mid] < elem)
        return BinarySearch(mid+1, high, elem);
    else
        return BinarySearch(low, mid-1, elem);
}
```

Time Required, for a problem of size n (worst case): $c_2 * \lg(n)$ for some constant c_2

02-16: Do Constants Matter?

- Linear Search requires time $c_1 * n$, for some c_1
- Binary Search requires time $c_2 * \lg(n)$, for some c_2

What if there is a *very* high overhead cost for function calls?

What if c_2 is *1000 times larger* than c_1 ?

02-17: Constants *Do Not Matter!*

Length of list	Time Required for Linear Search	Time Required for Binary Search
10	0.001 seconds	0.3 seconds
100	0.01 seconds	0.66 seconds
1000	0.1 seconds	1.0 seconds
10000	1 second	1.3 seconds
100000	10 seconds	1.7 seconds
1000000	2 minutes	2.0 seconds
10000000	17 minutes	2.3 seconds
10^{10}	11 days	3.3 seconds
10^{15}	30 centuries	5.0 seconds
10^{20}	300 million years	6.6 seconds

02-18: Growth Rate

We care about the *Growth Rate* of a function – how much more we can do if we add more processing power

Faster Computers \neq Solving Problems Faster
Faster Computers = Solving Larger Problems

- Modeling more variables
- Handling bigger databases
- Pushing more polygons

02-19: Growth Rate Examples

	Size of problem that can be solved					
time	$10n$	$5n$	$n \lg n$	n^2	n^3	2^n
1 s	1000	2000	1003	100	21	13
2 s	2000	4000	1843	141	27	14
20 s	20000	40000	14470	447	58	17
1 m	60000	120000	39311	774	84	19
1 hr	3600000	7200000	1736782	18973	331	25

02-20: Constants and Running Times

- When calculating a formula for the running time of an algorithm:
 - Constants aren't as important as the growth rate of the function
 - Lower order terms don't have much of an impact on the growth rate
 - $x^3 + x$ vs x^3
- We'd like a formal method for describing what is important when analyzing running time, and what is not.

02-21: Big-Oh Notation

$O(f(n))$ is the set of all functions that are bound from above by $f(n)$

$T(n) \in O(f(n))$ if

$\exists c, n_0$ such that $T(n) \leq c * f(n)$ when $n > n_0$

02-22: Big-Oh Examples

$$n \in O(n) ?$$

$$10n \in O(n) ?$$

$$n \in O(10n) ?$$

$$n \in O(n^2) ?$$

$$n^2 \in O(n) ?$$

$$10n^2 \in O(n^2) ?$$

$$n \lg n \in O(n^2) ?$$

$$\ln n \in O(2n) ?$$

$$\lg n \in O(n) ?$$

$$3n + 4 \in O(n) ?$$

$$5n^2 + 10n - 2 \in O(n^3) ? O(n^2) ? O(n) ?$$

02-23: Big-Oh Examples

$$n \in O(n)$$

$$10n \in O(n)$$

$$n \in O(10n)$$

$$n \in O(n^2)$$

$$n^2 \notin O(n)$$

$$10n^2 \in O(n^2)$$

$$n \lg n \in O(n^2)$$

$$\ln n \in O(2n)$$

$$\lg n \in O(n)$$

$$3n + 4 \in O(n)$$

$$5n^2 + 10n - 2 \in O(n^3), \in O(n^2), \notin O(n) ?$$

02-24: Big-Oh Examples II

$$\sqrt{n} \in O(n) ?$$

$$\lg n \in O(2^n) ?$$

$$\lg n \in O(n) ?$$

$$n \lg n \in O(n) ?$$

$$n \lg n \in O(n^2) ?$$

$$\sqrt{n} \in O(\lg n) ?$$

$$\lg n \in O(\sqrt{n}) ?$$

$$n \lg n \in O(n^{\frac{3}{2}}) ?$$

$$n^3 + n \lg n + n\sqrt{n} \in O(n \lg n) ?$$

$$n^3 + n \lg n + n\sqrt{n} \in O(n^3) ?$$

$$n^3 + n \lg n + n\sqrt{n} \in O(n^4) ?$$

02-25: Big-Oh Examples II

$$\sqrt{n} \in O(n)$$

$$\lg n \in O(2^n)$$

$$\lg n \in O(n)$$

$$n \lg n \notin O(n)$$

$$n \lg n \in O(n^2)$$

$$\sqrt{n} \notin O(\lg n)$$

$$\lg n \in O(\sqrt{n})$$

$$n \lg n \in O(n^{\frac{3}{2}})$$

$$n^3 + n \lg n + n\sqrt{n} \notin O(n \lg n)$$

$$n^3 + n \lg n + n\sqrt{n} \in O(n^3)$$

$$n^3 + n \lg n + n\sqrt{n} \in O(n^4)$$

02-26: Big-Oh Examples III

$$f(n) = \begin{cases} n & \text{for } n \text{ odd} \\ n^3 & \text{for } n \text{ even} \end{cases}$$
$$g(n) = n^2$$

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

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

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

$$f(n) \in O(n^3) ?$$

02-27: Big-Oh Examples III

$$f(n) = \begin{cases} n & \text{for } n \text{ odd} \\ n^3 & \text{for } n \text{ even} \end{cases}$$
$$g(n) = n^2$$

$$f(n) \notin O(g(n))$$

$$g(n) \notin O(f(n))$$

$$n \in O(f(n))$$

$$f(n) \in O(n^3)$$

02-28: Big- Ω Notation

$\Omega(f(n))$ is the set of all functions that are bound from *below* by $f(n)$

$T(n) \in \Omega(f(n))$ if

$\exists c, n_0$ such that $T(n) \geq c * f(n)$ when $n > n_0$

02-29: Big- Ω Notation

$\Omega(f(n))$ is the set of all functions that are bound from *below* by $f(n)$

$T(n) \in \Omega(f(n))$ if

$\exists c, n_0$ such that $T(n) \geq c * f(n)$ when $n > n_0$

$$f(n) \in O(g(n)) \Rightarrow g(n) \in \Omega(f(n))$$

02-30: Big- Θ Notation

$\Theta(f(n))$ is the set of all functions that are bound *both above and below* by $f(n)$. Θ is a *tight bound*

$T(n) \in \Theta(f(n))$ if

$$T(n) \in O(f(n)) \text{ and } T(n) \in \Omega(f(n))$$

02-31: Big-Oh Rules

1. If $f(n) \in O(g(n))$ and $g(n) \in O(h(n))$, then $f(n) \in O(h(n))$
2. If $f(n) \in O(kg(n))$ for any constant $k > 0$, then $f(n) \in O(g(n))$
3. If $f_1(n) \in O(g_1(n))$ and $f_2(n) \in O(g_2(n))$, then $f_1(n) + f_2(n) \in O(\max(g_1(n), g_2(n)))$
4. If $f_1(n) \in O(g_1(n))$ and $f_2(n) \in O(g_2(n))$, then $f_1(n) * f_2(n) \in O(g_1(n) * g_2(n))$

(Also work for Ω , and hence Θ)

02-32: Big-Oh Guidelines

- Don't include constants/low order terms in Big-Oh
- Simple statements: $\Theta(1)$
- Loops: $\Theta(\text{inside}) * \# \text{ of iterations}$
 - Nested loops work the same way
- Consecutive statements: Longest Statement
- Conditional (if) statements:
 $O(\text{Test} + \text{longest branch})$

02-33: Calculating Big-Oh

```
for (i=1; i<n; i++)  
    sum++;
```

02-34: Calculating Big-Oh

```
for (i=1; i<n; i++)      Executed n times
    sum++;               O(1)
```

Running time: $O(n)$, $\Omega(n)$, $\Theta(n)$

02-35: Calculating Big-Oh

```
for (i=1; i<n; i=i+2)
    sum++;
```

02-36: Calculating Big-Oh

```
for (i=1; i<n; i=i+2)
    sum++;
```

Executed $n/2$ times
 $O(1)$

Running time: $O(n)$, $\Omega(n)$, $\Theta(n)$

02-37: Calculating Big-Oh

```
for (i=1; i<n; i++)  
    for (j=1; j < n/2; j++)  
        sum++;
```

02-38: Calculating Big-Oh

for (i=1; i<n; i++)	Executed n times
for (j=1; j < n/2; j++)	Executed n/2 times
sum++;	O(1)

Running time: $O(n^2)$, $\Omega(n^2)$, $\Theta(n^2)$

02-39: Calculating Big-Oh

```
for (i=1; i<n; i=i*2)
    sum++;
```

02-40: Calculating Big-Oh

```
for (i=1; i<n; i=i*2)    Executed lg n times  
    sum++;              O(1)
```

Running Time: $O(\lg n)$, $\Omega(\lg n)$, $\Theta(\lg n)$

02-41: Calculating Big-Oh

```
for (i=0; i<n; i++)  
    for (j = 0; j<i; j++)  
        sum++;
```

02-42: Calculating Big-Oh

```
for (i=0; i<n; i++)           Executed n times
  for (j = 0; j<i; j++)       Executed <= n times
    sum++;                    O(1)
```

Running Time: $O(n^2)$. Also $\Omega(n^2)$?

02-43: Calculating Big-Oh

```
for (i=0; i<n; i++)  
    for (j = 0; j<i; j++)  
        sum++;
```

Exact # of times `sum++` is executed:

$$\sum_{i=1}^n i = \frac{n(n+1)}{2}$$
$$\in \Theta(n^2)$$

02-44: Calculating Big-Oh

```
sum = 0;
for (i=0; i<n; i++)
    sum++;
for (i=1; i<n; i=i*2)
    sum++;
```

02-45: Calculating Big-Oh

sum = 0;	$O(1)$
for (i=0; i<n; i++)	Executed n times
sum++;	$O(1)$
for (i=1; i<n; i=i*2)	Executed $\lg n$ times
sum++;	$O(1)$

Running Time: $O(n)$, $\Omega(n)$, $\Theta(n)$

02-46: Calculating Big-Oh

```
sum = 0;
for (i=0; i<n; i=i+2)
    sum++;
for (i=0; i<n/2; i=i+5)
    sum++;
```

02-47: Calculating Big-Oh

sum = 0;	$O(1)$
for (i=0; i<n; i=i+2)	Executed $n/2$ times
sum++;	$O(1)$
for (i=0; i<n/2; i=i+5)	Executed $n/10$ times
sum++;	$O(1)$

Running Time: $O(n)$, $\Omega(n)$, $\Theta(n)$

02-48: Calculating Big-Oh

```
for (i=0; i<n;i++)  
    for (j=1; j<n; j=j*2)  
        for (k=1; k<n; k=k+2)  
            sum++;
```

02-49: Calculating Big-Oh

for (i=0; i<n;i++)	Executed n times
for (j=1; j<n; j=j*2)	Executed lg n times
for (k=1; k<n; k=k+2)	Executed n/2 times
sum++;	$O(1)$

Running Time: $O(n^2 \lg n)$, $\Omega(n^2 \lg n)$, $\Theta(n^2 \lg n)$

02-50: Calculating Big-Oh

```
sum = 0;
for (i=1; i<n; i=i*2)
    for (j=0; j<n; j++)
        sum++;
```

02-51: Calculating Big-Oh

sum = 0;	$O(1)$
for (i=1; i<n; i=i*2)	Executed $\lg n$ times
for (j=0; j<n; j++)	Executed n times
sum++;	$O(1)$

Running Time: $O(n \lg n)$, $\Omega(n \lg n)$, $\Theta(n \lg n)$

02-52: Calculating Big-Oh

```
sum = 0;
for (i=1; i<n; i=i*2)
    for (j=0; j<i; j++)
        sum++;
```

02-53: Calculating Big-Oh

<code>sum = 0;</code>	<code>O(1)</code>
<code>for (i=1; i<n; i=i*2)</code>	Executed $\lg n$ times
<code>for (j=0; j<i; j++)</code>	Executed $\leq n$ times
<code>sum++;</code>	<code>O(1)</code>

Running Time: $O(n \lg n)$. Also $\Omega(n \lg n)$?

02-54: Calculating Big-Oh

```
sum = 0;
for (i=1; i<n; i=i*2)
    for (j=0; j<i; j++)
        sum++;
```

of times sum++ is executed:

$$\begin{aligned}\sum_{i=0}^{\lg n} 2^i &= 2^{\lg n + 1} - 1 \\ &= 2n - 1 \\ &\in \Theta(n)\end{aligned}$$

02-55: Calculating Big-Oh

Of course, a little change can mess things up a bit ...

```
sum = 0;
for (i=1; i<=n; i=i+1)
    for (j=1; j<=i; j=j*2)
        sum++;
```

02-56: Calculating Big-Oh

Of course, a little change can mess things up a bit ...

```
sum = 0;
for (i=1; i<=n; i=i+1)           Executed n times
    for (j=1; j<=i; j=j*2)       Executed  $\leq \lg n$  times
        sum++;                    $O(1)$ 
```

So, this code is $O(n \lg n)$ – but is it also $\Omega(n \lg n)$?

02-57: Calculating Big-Oh

Of course, a little change can mess things up a bit ...

```
sum = 0;
for (i=1; i<=n; i=i+1)           Executed n times
    for (j=1; j<=i; j=j*2)       Executed <= lg n times
        sum++;                   O(1)
```

Total time `sum++` is executed:

$$\sum_{i=1}^n \lg i$$

This can be tricky to evaluate, but we only need a bound ...

02-58: Calculating Big-Oh

Total # of times `sum++` is executed:

$$\begin{aligned}\sum_{i=1}^n \lg i &= \sum_{i=1}^{n/2-1} \lg i + \sum_{i=n/2}^n \lg i \\ &\geq \sum_{i=n/2}^n \lg i \\ &\geq \sum_{i=n/2}^n \lg n/2 \\ &= n/2 \lg n/2 \\ &\in \Omega(n \lg n)\end{aligned}$$