

# Efficient Algorithms

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Software Systems Engineering

TGGS

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# About Me

Ekkapot Charoenwanit

## Office:

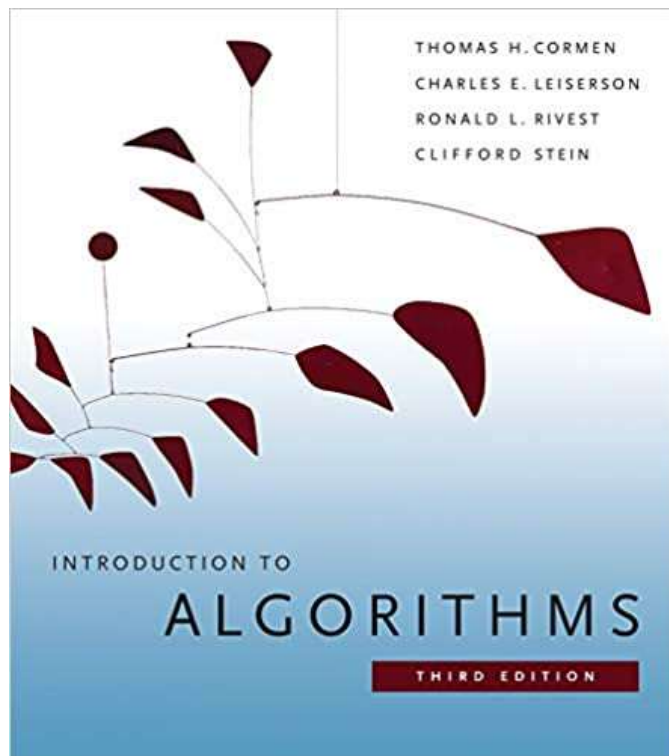
802/806

you will more likely find me in 806

## Office Hours:

Wednesday Afternoon 13:00-16:30

# Textbook known as *CLRS*



The *third edition* is recommended, but the *second edition* is also fine.

\*\*\*Available at the main library

# Course Logistics

Weekly Assignments	<b>50%</b>
Problem Sets	
Programming Labs	
Midterm Exam	<b>20%</b>
Final Exam	<b>30%</b>

**\*\*\*Turning in an assignment late = 10% off per day**



## Grading Scale:

**A [80-100]**

**B [70-80)**

**C [60-70)**

**D [50-60)**

**F  $(-\infty, 50)$**

# Course Contents

- Asymptotic Analysis
- Induction and Recurrence Relations
- Data Structures
- Searching and Sorting Algorithms
- Divide and Conquer
- Dynamic Programming
- Greedy Algorithms
- Graph Algorithms
- State Space Search
- NP-Completeness
- Approximation Algorithms
- Randomised Algorithms
- Linear Programming
- More advanced topics if time allows

# The Hierarchy of Abstraction in Computing



This course spans these 3 abstraction layers:

- Problem
- Algorithm
- Programming Language

Our focus will be on the **Algorithm** layer.

# Lecture 1: Algorithm Analysis and Asymptotic Notations

# Definition of Algorithms

An algorithm is a finite, unambiguous description for a sequence of computational steps to solve a computational problem.

- ***Finite*** in this context means the algorithm must eventually terminate.



# Algorithmic Complexity

How *efficient* an algorithm is can be measured by its *algorithmic complexity*

- Time Complexity (Temporal)

How many computational step units are required?

How much time does the algorithm need?

- Space Complexity (Spatial)

How much space does the algorithm need?

This course will focus more on Time Complexity.

# Performance Analysis of Algorithms

There are generally **two** methods for analyzing algorithms' performance:

- **Experimental Analysis:**
  - Run code on a computer
  - Measure the running time for different problem sizes
  - Plot the result as a graph
- **Mathematical Analysis:**
  - Express the number of elementary steps parameterized by the problem size

# Selection Sort

---

```
1: procedure SELECTIONSORT( $d, n$ )
2:   for  $k = n$  ;  $k > 1$  ;  $k --$  do
3:      $maxI = 1$ 
4:     for  $i = 2$  ;  $i \leq k$  ;  $i ++$  do
5:       if  $d[i] > d[maxI]$  then
6:          $maxI = i$ 
7:        $d[k] \iff d[maxI]$ 
```

# Experimental Analysis

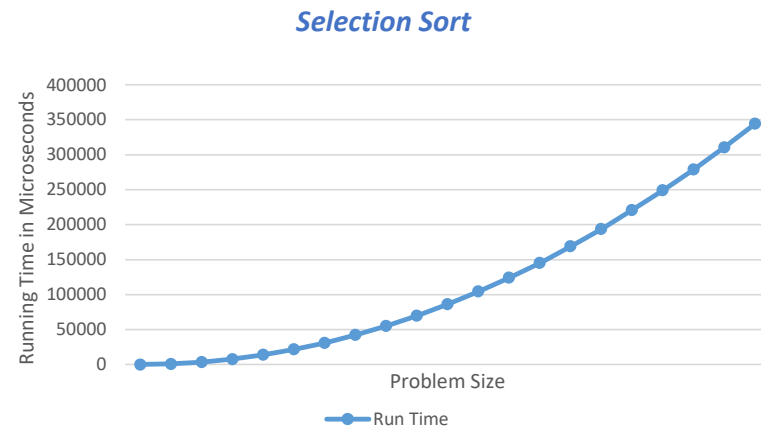
Running a C++ implementation of selection sort for  $n = 0$  to **20000** on my workstation:

*Ubuntu 18*

*Intel Core-i7-7700 CPU @3.60GHz*

*with 16 GB of RAM*

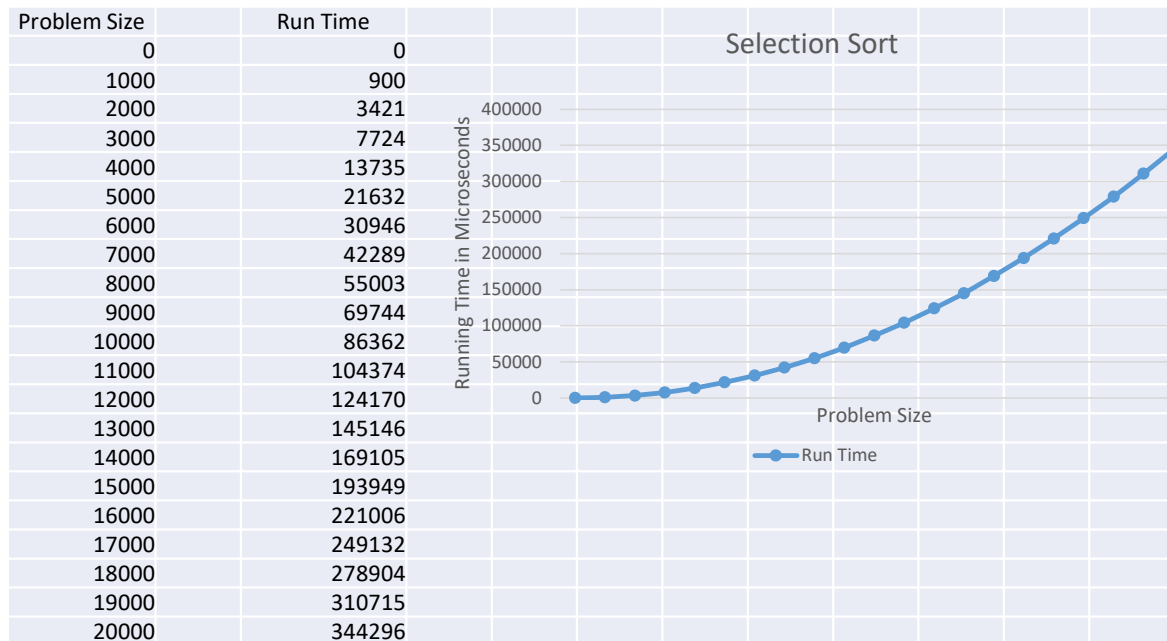
yielded the plot on the right.



The running time appears to be quadratic in problem size:

$$T(n) = 8.60 \times 10^{-4}n^2$$

# Experimental Analysis



- The code was run for different numbers of elements  $n$  between 0 and 20,000 with a step increase of 1,000.
- Each problem size was run for 100 times and the running times were averaged.

# Mathematical Analysis

The time complexity of an algorithm can be determined by the total number of *elementary operations* executed.

$$Time \propto \#Elementary\ Operations$$

*Elementary Operations* are operations whose execution time is bounded by a *constant*, which depends on

- Programming Language
- Compiler
- Machine

# Approaches to Counting Elementary Operations

- Count every elementary operations
  - impractical
- Count only **representative** elementary operations
  - executed the most number of times
  - called **barometer operations**

---

```
1: procedure SELECTIONSORT( $d, n$ )
2:   for  $k = n$  ;  $k > 1$  ;  $k --$  do
3:      $maxI = 1$ 
4:     for  $i = 2$  ;  $i \leq k$  ;  $i ++$  do
5:       if  $d[i] > d[maxI]$  then
6:          $maxI = i$ 
7:        $d[k] \iff d[maxI]$ 
```

What are the barometer operations in the code of selection sort shown on the right?

# Approaches to Counting Elementary Operations

- Count every elementary operations
  - impractical
- Count only **representative** elementary operations
  - executed the most number of times
  - called **barometer operations**

---

```
1: procedure SELECTIONSORT( $d, n$ )
2:   for  $k = n$  ;  $k > 1$  ;  $k - -$  do
3:      $maxI = 1$ 
4:     for  $i = 2$  ;  $i \leq k$  ;  $i ++$  do
5:       if  $d[i] > d[maxI]$  then
6:          $maxI = i$ 
7:        $d[k] \iff d[maxI]$ 
```

Barometer :  $d[i] > d[maxI]$



# Approaches to Counting Elementary Operations

Count the number of times  $d[i] > d[maxI]$  is executed

Inner Loop

$$\sum_{i=2}^k 1$$

---

```
1: procedure SELECTIONSORT( $d, n$ )
2:   for  $k = n$  ;  $k > 1$  ;  $k --$  do
3:      $maxI = 1$ 
4:     for  $i = 2$  ;  $i \leq k$  ;  $i ++$  do
5:       if  $d[i] > d[maxI]$  then
6:          $maxI = i$ 
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```

# Approaches to Counting Elementary Operations

Count the number of times  $d[i] > d[maxI]$  is executed

Outer Loop

$$\sum_{k=2}^n$$

Inner Loop

$$\sum_{i=2}^k 1$$

---

```
1: procedure SELECTIONSORT( $d, n$ )
2:   for  $k = n$  ;  $k > 1$  ;  $k --$  do
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5:       if  $d[i] > d[maxI]$  then
6:          $maxI = i$ 
7:        $d[k] \iff d[maxI]$ 
```

# Approaches to Counting Elementary Operations

Count the number of times  $d[i] > d[maxI]$  is executed

$$\sum_{k=n}^2 \sum_{i=2}^k 1 = \sum_{k=1}^{n-1} \sum_{i=1}^{k-1} 1 = \sum_{k=1}^{n-1} (k-1) = \frac{(n-1)(n)}{2}$$

---

```
1: procedure SELECTIONSORT( $d, n$ )
2:   for  $k = n$  ;  $k > 1$  ;  $k --$  do
3:      $maxI = 1$ 
4:     for  $i = 2$  ;  $i \leq k$  ;  $i ++$  do
5:       if  $d[i] > d[maxI]$  then
6:          $maxI = i$ 
7:        $d[k] \iff d[maxI]$ 
```

Therefore, the running time of selection sort is proportional to  $\frac{(n-1)(n)}{2}$ .

# Complexity Growth of Selection Sort

---

```
1: procedure SELECTIONSORT( $d, n$ )
2:   for  $k = n$  ;  $k > 1$  ;  $k --$  do
3:      $maxI = 1$ 
4:     for  $i = 2$  ;  $i \leq k$  ;  $i ++$  do
5:       if  $d[i] > d[maxI]$  then
6:          $maxI = i$ 
7:        $d[k] \iff d[maxI]$ 
```

We say that the time complexity of selection sort exhibits a ***quadratic growth*** in the number of elements  $n$ .

# Complexity Growth

The complexity of an algorithm is generally represented as a function of its *input size* (and possibly the values of other parameters).

Such functions are restricted to *real-valued functions*  $f(n): \mathbb{N} \mapsto \mathbb{R}$  defined on the *non-negative integers* that are *eventually* positive as there exists an integer  $n_0$  such that  $f(n) > 0$  for all  $n \geq n_0$ .

The growth function  $f(n)$

- gives a simple characterization of the algorithm's efficiency
- gives a simple relative efficiency comparison with other algorithms

# Asymptotic Analysis

## Benefits of Asymptotic Analysis

- Provides machine-independent analysis
- Abstracts away from implementation details
- Focuses only on the dominating factors

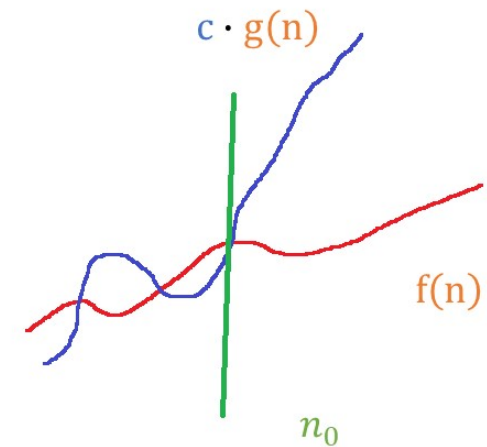
For *sufficiently large* input sizes, a linear-time algorithm with a moderately big constant overhead will eventually run faster than a quadratic-time one with a relatively small constant overhead.

# Definition of Big O

A function  $f(n)$  is in  $O(g(n))$  if and only if

$$\exists c \in \mathbb{R}^+ \exists n_0 \in \mathbb{N} ( \forall n \in \mathbb{N} : n \geq n_0 \mapsto f(n) \leq c g(n) )$$

$f(n)$  is bound from above by  $g(n)$  up to a constant factor  $c$  for all sufficiently large  $n$  beyond  $n_0$ .



# Big-O Notation

$O(g(n))$  is a set of functions taking a *real natural number* as input and returning a *real number*.

$$O(g(n)) = \{f: \mathbb{N} \mapsto \mathbb{R} : \\ \exists c \in \mathbb{R}^+ \exists n_0 \in \mathbb{N} ( \forall n \in \mathbb{N} : n \geq n_0 \rightarrow f(n) \leq c g(n) ) \}$$

Therefore,

$$f(n) = O(g(n)) \text{ actually means } f(n) \in O(g(n))$$

But it is also common in the literature to use  $f(n) = O(g(n))$ .



## Proving $f(n) = O(g(n))$

Proving that  $f(n) = O(g(n))$  is about intelligently picking  $c$  and  $n_0$ .

$$2n^2 = O(n^2)$$

Converting the above notation into the corresponding inequality gives:

$$2n^2 \leq cn^2 \text{ for all } n \geq n_0$$

All we have to do is to show that there is at least a pair of  $(c, n_0)$  that satisfies the inequality above.

## Proving $f(n) = O(g(n))$

$$2n^2 \leq cn^2 \text{ for all } n \geq n_0$$

Since we know that  $n^2$  is non-negative, choosing  $n > 0$  and dividing both sides by  $n^2$  gives:

$$c \geq 2$$

Therefore, the above inequality will hold if  $n > 0$  and  $c \geq 2$

Therefore, we can choose  $n_0 = 1$  and  $c = 2$  ■

**NB:** we could have chosen other values such as  $n_0 = 2$  and  $c = 10$ .

## A little harder claim

Show that  $2n^2 + 3 = O(n^2)$ .

Converting the notation into the corresponding inequality gives:

$$2n^2 + 3 \leq cn^2 \text{ for all } n \geq n_0$$

The easy but \*impulsive\* way:

Try  $c = 5$  and solve for  $n$ :

$$2n^2 + 3 \leq 5n^2$$

$$3 \leq 3n^2$$

$$1 \leq n^2$$

$$1 \leq n \quad (\text{NB: the negative values are ignored.})$$

Therefore, we choose  $c = 5$  and  $n_0 = 1$ . ■

# Another approach

The more systematic way:

Solve for  $n$ :

$$2n^2 + 3 \leq cn^2$$

Rearranging gives

$$3 \leq (c - 2)n^2$$

Assuming  $c - 2 > 0 \rightarrow c > 2$ ,

$$\frac{3}{c-2} \leq n^2$$

$$\sqrt{\frac{3}{c-2}} \leq n$$

Now we can choose  $c > 2$  that makes  $n$  look simple.

$c = 5$  leads to:  $1 \leq n$

Therefore, the most obvious choice of  $n_0$  is  $n_0 = 1$ .

Therefore, we choose  $c = 5$  and  $n_0 = 1$  ■

## Not hard enough?

Show that  $7n^2 + 1000n = O(n^2)$ .

$$7n^2 + 1000n \leq cn^2 \text{ for all } n \geq n_0$$

$$(c-7)n^2 \geq 1000n$$

Assume  $c - 7 > 0 \rightarrow c > 7$ .

Consider only  $n > 0$  and divide both sides by  $n$ .

$$(c - 7)n \geq 1000$$

$$n \geq \frac{1000}{c-7}$$

Therefore, we choose  $c = 8$  and  $n_0 = 1000$  ■

# Not hard enough?

Show that  $7n^2 - 1000n = O(n^2)$ .

$$\begin{aligned} 7n^2 - 1000n &\leq cn^2 \text{ for all } n \geq n_0 \\ -1000n &\leq (c - 7)n^2 \end{aligned}$$

Assume  $c - 7 > 0 \rightarrow c > 7$ .

Consider only  $n > 0$  and divide both sides by  $n$ .

$$\begin{aligned} -1000 &\leq (c - 7)n \\ n &\geq \frac{-1000}{c - 7} \quad (\text{NB: the sign does not flip b/c } c - 7 > 0) \\ n &\geq \frac{1000}{7 - c} \end{aligned}$$

Therefore, we choose  $c = 8$ , leading to  $n \geq -1$ .

Since  $n > 0$ , we choose  $c = 8$  and  $n_0 = 1$  ■

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

We must show that the negation of  $\exists c \in \mathbb{R}^+ \exists n_0 \in \mathbb{N} ( \forall n \in \mathbb{N} : n \geq n_0 \rightarrow f(n) \leq cg(n) )$  holds.

The negation is:

$$\forall c \in \mathbb{R}^+ \forall n_0 \in \mathbb{N} ( \exists n \in \mathbb{N} : n \geq n_0 \wedge f(n) > cg(n) )$$

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

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

$$\forall c \in \mathbb{R}^+ \forall n_0 \in \mathbb{N} (\exists n \in \mathbb{N} : n \geq n_0 \wedge n^2 > c \cdot n)$$

Solve for  $n$ :

$$n \geq n_0 \text{ and } n^2 > c \cdot n$$

$$n \geq n_0 \text{ and } n > c$$

$$n > \max(n_0, c)$$

Therefore, we can choose  $n = \max(n_0, \lceil c \rceil) + 1$  ■



# Comparing Polynomial Functions

For a **polynomial**  $f(n)$ , it is easy to figure out a Big-O class  $f(n)$  belongs to.

- It is the term with the **highest degree** !!!
  - $f(n) = 3n^5 + 40n^2 + 100n + 2 \in O(n^5)$
- It is perfectly valid to use a more slacking upper bound
  - $f(n) \in O(n^6)$
  - $f(n) \in O(n^{1,000,000})$

**\*\*\*Exercise:** Show that  $f(n) = a_k n^k + a_{k-1} n^{k-1} + \dots + a_1 n + a_0 \in O(n^k)$  if  $a_k > 0$  and  $k > 0$ .

# Comparing Polynomial Functions

$n$	$n/2$	$n^2/2$	$\frac{(n-1)(n)}{2}$	$n^2$
10	5	50	45	100
1,000	500	500,000	499,500	1,000,000
10,000	5000	50,000,000	49,995,000	100,000,000
100,000	50,000	5,000,000,000	4,999,950,000	10,000,000,000

Table comparing linear and quadratic growth

# Properties of Big-O

- $f(n) \in O(cf(n))$ 
  - Big-O is conserved under multiplicative constant.
- $f(n) \in O(g(n)) \wedge g(n) \in O(h(n)) \Rightarrow f(n) \in O(h(n))$ 
  - Big-O is transitive.

and many more ...

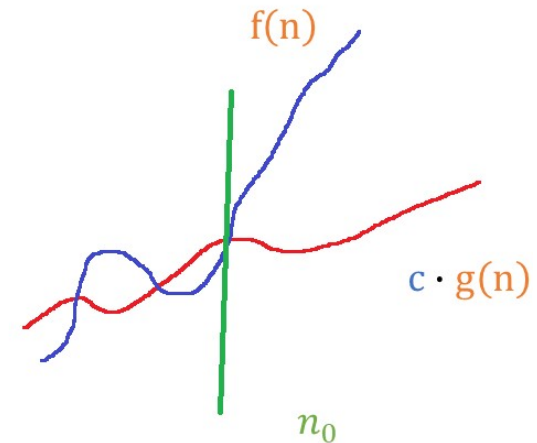
**\*\*\*Exercise:** Show that the properties above always hold.

# Definition of Big Omega

A function  $f(n)$  is in  $\Omega(g(n))$  if and only if

$$\exists c \in \mathbb{R}^+ \exists n_0 \in \mathbb{N} ( \forall n \in \mathbb{N} : n \geq n_0 \rightarrow f(n) \geq c \cdot g(n) )$$

$f(n)$  is bound from below by  $cg(n)$  for all sufficiently large  $n$  beyond  $n_0$ .



# Big-Omega Notation

$\Omega(g(n))$  is a set of functions taking a *real natural number* as input and returning a *real number*.

$$\Omega(g(n)) = \{f: \mathbb{N} \mapsto \mathbb{R} : \exists c \in \mathbb{R}^+ \exists n_0 \in \mathbb{N} ( \forall n \in \mathbb{N} : n \geq n_0 \rightarrow f(n) \geq c g(n) )\}$$

Therefore,

$$f(n) = \Omega(g(n)) \text{ actually means } f(n) \in \Omega(g(n))$$

But it is also common in the literature to use  $f(n) = \Omega(g(n))$ .

## Proving $f(n) = \Omega(g(n))$

Proving that  $f(n) = \Omega(g(n))$  is about intelligently picking  $c$  and  $n_0$ .

$$2n^2 = \Omega(n)$$

Converting the above notation into the corresponding inequality gives:

$$2n^2 \geq cn \text{ for all } n \geq n_0$$

All we have to do is to show that there is at least a pair of  $(c, n_0)$  that satisfies the inequality above.

## Proving $f(n) = \Omega(g(n))$

$$2n^2 \geq cn \text{ for all } n \geq n_0$$

Assuming  $n > 0$  and dividing both sides by  $n$  gives:

$$\begin{aligned} 2n &\geq c \\ n &\geq \frac{c}{2} \end{aligned}$$

Therefore, the above inequality will hold if  $n \geq \max(1, \lceil \frac{c}{2} \rceil)$  and  $c > 0$ .

Therefore, we can choose  $n_0 = 1$  and  $c = 2$  ■

**NB:** we could have chosen other values such as  $n_0 = 5$  and  $c = 10$ .

# Big-Omega of Polynomials

\*\*\*Exercise:

$f(n) = a_k n^k + a_{k-1} n^{k-1} + \dots + a_1 n + a_0 \in \Omega(n^k)$  if  $a_k > 0$   
and  $k > 0$ .



# Properties of Big-Omega

- $f(n) \in \Omega(cf(n))$ 
  - Big-Omega is conserved under multiplicative constant.
- $f(n) \in \Omega(g(n)) \wedge g(n) \in \Omega(h(n)) \Rightarrow f(n) \in \Omega(h(n))$ 
  - Big-Omega is transitive.

and many more ...

**\*\*\*Exercise:** Show that the properties above always hold.

# Definition of Big Theta

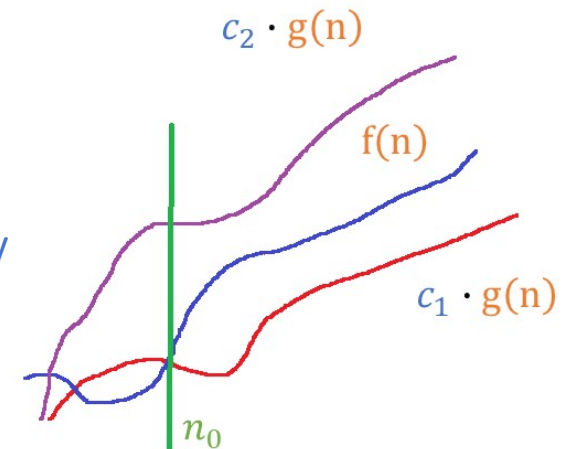
A function  $f(n)$  is in  $\Theta(g(n))$  if and only if

$$\exists c_1 \in \mathbb{R}^+ \exists c_2 \in \mathbb{R}^+ \exists n_0 \in \mathbb{N} ( \forall n \in \mathbb{N} : n \geq n_0 \rightarrow c_1 \cdot g(n) \leq f(n) \leq c_2 \cdot g(n) )$$

$f(n)$  is sandwiched  
between  $c_1 g(n)$  and  
 $c_2 g(n)$  for all sufficiently large  $n$  beyond  $n_0$

$f(n)$  grows at the same rate as  $g(n)$  in the sense that  $f(n)$  is eventually squeezed between two constant multiples of  $g(n)$ .

$$\Theta(g(n)) = \Omega(g(n)) \cap O(g(n))$$



## Proving $f(n) = \Theta(g(n))$

Show that  $\frac{n^2}{2} - 3n = \Theta(n^2)$

$$c_1 n^2 \leq \frac{n^2}{2} - 3n \leq c_2 n^2 \text{ for all } n \geq n_0$$

Dividing both sides by  $n^2 > 0$  gives:

$$c_1 \leq \frac{1}{2} - \frac{3}{n} \leq c_2$$

## Proving $f(n) = \Theta(g(n))$

Lower Bound:

$$c_1 \leq \frac{1}{2} - \frac{3}{n}$$

$$c_1 \leq \frac{n-6}{2n}$$

$$n(1 - 2c_1) \geq 6$$

Assuming  $1 - 2c_1 > 0 \rightarrow c_1 < \frac{1}{2}$

$$n \geq \frac{6}{1-2c_1}$$

Choose  $c_1 = \frac{1}{4}, n_{01} = 12$ .

We have just proven  $f(n) = \Omega(g(n))$  as a by-product.

## Proving $f(n) = \Theta(g(n))$

Upper Bound:

$$\frac{1}{2} - \frac{3}{n} \geq c_2$$

$$c_2 \geq \frac{n-6}{2n}$$

$$n(1 - 2c_2) \geq 6$$

Assuming  $1 - 2c_2 < 0 \rightarrow c_2 > \frac{1}{2}$

$$n \geq \frac{6}{1-2c_2}$$

Choose  $c_2 = 1$ ,  $n_0 = 1$ .

We have just proven  $f(n) = O(g(n))$  as a by-product.

Proving  $f(n) = \Theta(g(n))$

Therefore,  $c_1 = \frac{1}{4}$ ,  $c_2 = 1$ ,  $n_0 = \max(n_{01}, n_{02}) = \max(12, 1) = 12$  ■

# Properties of Big Theta

- $f(n) \in \Theta(f(n))$  (Reflexive)
  - $f(n)$  has the same order as itself.
- $f(n) \in \Theta(g(n)) \Rightarrow g(n) \in \Theta(f(n))$  (Symmetric)
  - $f(n)$  has the same order as  $g(n)$ , then  $g(n)$  has the same order as  $f(n)$ .
- $f(n) \in \Theta(g(n)) \wedge g(n) \in \Theta(h(n)) \Rightarrow f(n) \in \Theta(h(n))$  (Transitive)
  - $f(n)$  has the same order as  $g(n)$ , and  $g(n)$  has the same order as  $h(n)$ , then  $f(n)$  has the same order as  $h(n)$ .

# Orders of Growth

$$\begin{aligned} O(1) \subset O(\log n) \subset O(n) \subset O(n \log n) \subset O(n^2) \\ \subset O(n^3) \subset O(2^n) \subset O(3^n) \subset O(n!) \end{aligned}$$

Proofs involving ***non-polynomial*** functions may require ***mathematical induction***.

We will cover induction in the next lecture.