

## 02 - Computational Complexity Analysis

[KOMS119602] & [KOMS120403]

Design and Analysis of Algorithm (2021/2022)

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# Euclidean algorithm to compute gcd

From last week...

## Computing gcd:

- Input: two integers  $a$  and  $b$
- Output: the greatest common divisor of  $m$  and  $n$

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### Algorithm 1 Naive gcd algorithm of two integers

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```
1: procedure GCD( $a, b$ )  
2:    $r = 1$   
3:    $x = \min(a, b)$   
4:   for  $i = 1$  to  $x$  do  
5:     if  $a \bmod i == 0$  and  $b \bmod i == 0$  then  $r = i$   
6:     end if  
7:   end for  
8: end procedure
```

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Complexity? homework!

# Euclidean algorithm to compute gcd

**From last week...**

## Example

Using the Euclidean algorithm, find the gcd of 210 and 45.

**Solution:**

$$210 = 4 \cdot 45 + 30$$

$$45 = 1 \cdot 30 + 15$$

$$30 = 2 \cdot 15 + 0$$

So  $\gcd(210, 45) = 15$

# Euclidean algorithm to compute gcd

From last week...

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## Algorithm 2 Euclidean algorithm

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```
1: procedure EUCLIDGCD( $a, b$ )  
2:   while  $b \neq 0$  do  
3:      $r = a \bmod b$   
4:      $a = b$   
5:      $b = r$   
6:   end while  
7:   return  $a$   
8: end procedure
```

---

Why does it terminate?

**Complexity?** homework!

# Computational complexity model

Can you recall what is **complexity** of an algorithm,  
and why should we study it?

# Computational complexity model

A part of *algorithm analysis* is computing the *computational complexity* of an algorithm.

The **computational complexity** or simply **complexity** of an algorithm is the amount of resources (*time* and *memory*) required to run it.

- **Time efficiency**: how fast an algorithm is executed
- **Space efficiency**: how much memory needed to execute an algorithm

How do we compute the complexity of an algorithm?

# Computational complexity model

## Example

Let a supercomputer executes an algorithm A, and a PC executes an algorithm B. Both computers have to sort an array of 1 million elements. The supercomputer can execute 100 million instructions in one second, while the PC is only able to execute 1 million instructions in one second.

Algorithm A needs  $2n^2$  instructions to sort  $n$  elements, and algorithm B needs  $50n \log n$  instructions. Compute the amount of time to sort 1 million elements in each computer!

# Computational complexity model

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Algorithm A needs  $2n^2$  instructions to sort  $n$  elements, and algorithm B needs  $50n \log n$  instructions. Compute the amount of time to sort 1 million elements in each computer!

## Solution:

- Supercomputer:  $\frac{2 \cdot (10^6)^2 \text{ instructions}}{10^8 \text{ instructions / sec}} = 20000 \text{ sec} \approx 5.56 \text{ hours}$
- PC:  $\frac{50 \cdot 10^6 \log 10^6 \text{ instructions}}{10^6 \text{ instructions / sec}} \approx 1000 \text{ sec} \approx 16.67 \text{ minutes}$

*Remark.* So, the number of executions matters!



## What affects computational complexity?

Time (and space) complexity depends on lots of things like *hardware, OS, processors, programming language and compiler*, etc. But we don't consider any of these factors when analyzing the algorithm.

### Remarks:

- Our focus on this subject will be on **time complexity**.
- We assume that our machine uses only one processor (i.e. *generic one-processor*).
- Time complexity is computed based on **the number of operations/instructions**
- The running time of an algorithm increases (or remains constant in case of constant running time) as the input size ( $n$ ) increases.

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**Algorithm 3** Average of an array of integers

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```
1: procedure AVERAGE( $A[1..n]$ )
2:    $\text{sum} \leftarrow 0$ 
3:   for  $i = 1$  to  $n$  do
4:      $\text{sum} \leftarrow \text{sum} + A[i]$ 
5:   end for
6:    $\text{avg} \leftarrow \text{sum}/n$ 
7: end procedure
```

---

The number of operations:

- Assignment: lines 2, 4, 6; with  $1 + n + 1 = n + 2$  operations
- Summation: line 4, with  $n$  operations
- Division: line 6, with 1 operation

**Complexity:**  $T(n) = (n + 2) + n = 2n + 2$  operations.

# Computational complexity model

Three measurements of resource usage:

- **Worst-case** ( $T_{\max}(n)$ ): it measures the resources (e.g. running time, memory) that an algorithm requires in the **worst case** i.e. **most difficult case**, given an input of arbitrary size  $n$  (usually denoted in asymptotic notation).
- **Best-case** ( $T_{\min}(n)$ ): describe an algorithm's behavior under **optimal conditions**.
- **Average-case** ( $T_{\text{avg}}(n)$ ): the amount of computational time used by the algorithm, **averaged over all possible inputs**.

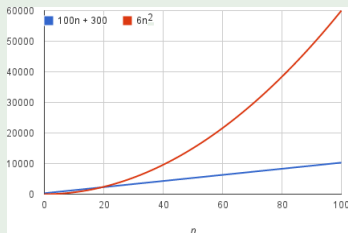
# Asymptotic notation and order of magnitude

- The running time of an algorithm is measured as a *function of the size of its input*.
- **Rate of growth** of the running time measures how fast a function grows with the input size. **Asymptotically** means the function matters *only for large values of  $n$* .
- The **order of magnitude** function describes the part of the function that increases the fastest as the value of  $n$  increases.

# Asymptotic notation and order of magnitude

## Example

Suppose that an algorithm, running on an input of size  $n$ , takes  $6n^2 + 100n + 300$ .



We only keep the **most significant term**. We say that the function  $6n^2$  has a higher order of magnitude than  $100n + 300$ .

# Big- $\mathcal{O}$ notation (asymptotic upper-bound)

Worst-case complexity measures the resources an algorithm needs in the *worst-case*. It gives an **upper bound** on the resources required by the algorithm.

## Why learn worst-case complexity?

- provides information about the maximum resource requirements
- naturally, it often happens in a system

# Big- $\mathcal{O}$ notation (asymptotic upper-bound)

**Big-O ( $\mathcal{O}(\cdot)$ ) notation:** a mathematical notation that describes the limiting behavior of a function when the argument tends towards a particular value or infinity.

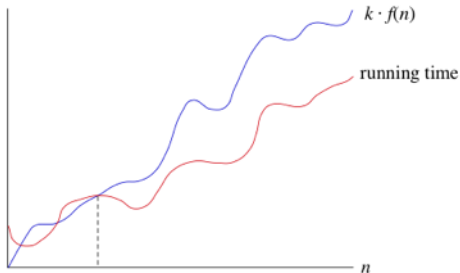
## Definition

$g(n) \in \mathcal{O}(f(n))$  if  $\exists k > 0$  and  $n_0$  s.t.  $g(n) \leq k \cdot f(n)$ ,  $\forall n \geq n_0$ .

# Big- $\mathcal{O}$ notation (asymptotic upper-bound)

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# Big- $\mathcal{O}$ notation (linear and polynomial functions)

## Example

Show that  $g(n) = 5n + 3$  is in  $\mathcal{O}(n)$ .

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## Solution:

Note that  $5n + 3 \leq 5n + 3n = 8n$  for all  $n \geq 1$ . In this case,  $k = 8$  and  $n_0 = 1$ . So,  $g(n) \in \mathcal{O}(n)$ .

# Big- $\mathcal{O}$ notation (linear and polynomial functions)

## Example

Show that  $g(n) = 3n^2 - 5n + 6$  is in  $\mathcal{O}(n^2)$ .

# Big- $\mathcal{O}$ notation (linear and polynomial functions)

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Show that  $g(n) = 3n^2 - 5n + 6$  is in  $\mathcal{O}(n^2)$ .

## Solution:

Note that  $3n^2 - 5n + 6 \leq 3n^2 + 0 + 6n^2 = 9n^2$  for all  $n \geq 1$ . In this case,  $k = 9$  and  $n_0 = 1$ . So,  $g(n) \in \mathcal{O}(n^2)$ .

# Big- $\mathcal{O}$ notation (linear and polynomial functions)

We denote by  $T(n)$  a function of time complexity.

## Theorem (Big- $\mathcal{O}$ of a polynomial complexity)

*If  $T(n) = a_m n^m + a_{m-1} n^{m-1} + \dots + a_1 n + a_0$  is a polynomial of order  $m$ , then  $T(n) \in \mathcal{O}(n^m)$ .*

## Theorem (Arithmetic operations on Big- $\mathcal{O}$ )

*Let  $T_1(n) \in \mathcal{O}(f(n))$  and  $T_2(n) \in \mathcal{O}(g(n))$ , then:*

- ①  $T_1(n) + T_2(n) \in \mathcal{O}(f(n)) + \mathcal{O}(g(n)) \in \mathcal{O}(\max(f(n), g(n)))$
- ②  $T_1(n)T_2(n) \in \mathcal{O}(f(n))\mathcal{O}(g(n)) \in \mathcal{O}(f(n)g(n))$
- ③  $\mathcal{O}(cf(n)) \in \mathcal{O}(f(n))$ , where  $c$  is a constant
- ④  $f(n) \in \mathcal{O}(f(n))$

**Proof:** homework!

## Example (Arithmetic operations on Big- $\mathcal{O}$ )

- ❶ Let  $T_1(n) \in \mathcal{O}(n)$  and  $T_2(n) \in \mathcal{O}(n^2)$ , then:

$$T_1(n) + T_2(n) \in \mathcal{O}(\max(n, n^2)) \in \mathcal{O}(n^2)$$

- ❷ Let  $T_1(n) \in \mathcal{O}(n)$  and  $T_2(n) \in \mathcal{O}(n^2)$ , then:

$$T_1(n)T_2(n) \in \mathcal{O}(n \cdot n^2) = \mathcal{O}(n^3)$$

- ❸  $\mathcal{O}(5n^2) \in \mathcal{O}(n^2)$

- ❹  $n^2 \in \mathcal{O}(n^2)$

## Review logarithms and exponents

$$\log_b a = c \Leftrightarrow b^c = a$$

- $a > 0$  is the power
- $b > 0$  is the base
- $c$  is the exponent

**Remark.** If the base  $b = 2$ , then it is called **binary logarithm**. The base is often omitted.

# Big- $\mathcal{O}$ notation (logarithmic function)

In Computer Science, we usually use **base-two** logarithm complexity by default. Why?



# Big- $\mathcal{O}$ notation (logarithmic function)

In Computer Science, we usually use **base-two** logarithm complexity by default. Why?

- It is common to work with binary numbers or divide input data in half
- In Big- $\mathcal{O}$  notation (upper bound growth), all logarithms are *asymptotically equivalent* (the only difference is there multiplicative constant factor)
- So, we do not specify the base, and only write it as  $\mathcal{O}(\log n)$

## Some properties of logarithmic function

- $\log_b 1 = 0$  for any  $b \geq 0$
- **Change of bases:**  $\log_b a = \frac{\log_p a}{\log_p b}$
- **Addition:**  $\log_p m + \log_p n = \log_p mn$
- **Subtraction:**  $\log_p m - \log_p n = \log_p \frac{m}{n}$
- **Power:**  $\log_p a^x = x \cdot \log_p a$
- **Inverse:**  $\log_p \frac{1}{a} = -\log_p a$
- Many others...

# Big- $\mathcal{O}$ notation (logarithmic function)

## Example

Show that  $g(n) = (n + 3) \log(n^2 + 1) + 2n^2$  is in  $\mathcal{O}(n^2)$

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Show that  $g(n) = (n + 3) \log(n^2 + 1) + 2n^2$  is in  $\mathcal{O}(n^2)$

### Solution:

Note that:

$$\log(n^2 + 1) \leq \log(2n^2) = \log 2 + \log n^2 \leq 2 \log n^2 = 4 \log n.$$

So,  $\log(n^2 + 1) \in \mathcal{O}(\log n)$ .

Since  $n + 3 \in \mathcal{O}(n)$ , then

$$(n + 3) \log(n^2 + 1) \in \mathcal{O}(n) \cdot \mathcal{O}(\log n) \in \mathcal{O}(n \log n).$$

Since  $2n^2 \in \mathcal{O}(n^2)$ , and  $\max(n \log n, n^2) = n^2$ , then  $g(n) \in \mathcal{O}(n^2)$ .

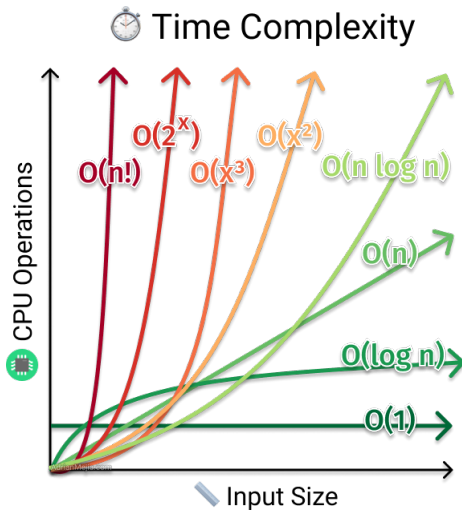
# Big- $\mathcal{O}$ notation (classification of algorithms)

The classification of algorithms based on the worst-time complexity

Complexity	Class
$\mathcal{O}(1)$	constant
$\mathcal{O}(\log n)$	logarithmic
$\mathcal{O}(n)$	linear
$\mathcal{O}(n \log n)$	quasi-logarithmic
$\mathcal{O}(n^2)$	square
$\mathcal{O}(n^3)$	cubic
$\mathcal{O}(n^k), k \geq 2$	polynomial
$\mathcal{O}(2^n)$	exponential
$\mathcal{O}(n!)$	factorial

$$\underbrace{\mathcal{O}(1) < \mathcal{O}(\log n) < \mathcal{O}(n) < \mathcal{O}(n \log n) < \mathcal{O}(n^2) < \mathcal{O}(n^3) < \dots < \mathcal{O}(2^n)}_{\text{polynomial algorithms}} < \underbrace{\mathcal{O}(n!)}_{\text{exponential algorithms}}$$

# Big- $\mathcal{O}$ notation (classification of algorithms)



# Big- $\mathcal{O}$ notation (determining asymptotic complexity)

- 1 **Assignment of values** (*comparison, arithmetic operations, read, write*) needs  $\mathcal{O}(1)$
- 2 **Accessing** an element of an array, or selecting a field from a record needs  $\mathcal{O}(1)$

## Example

- $\text{read}(x) \rightarrow \mathcal{O}(1)$
- $x : x + a[k] \rightarrow \mathcal{O}(1)$
- $\text{print}(x) \rightarrow \mathcal{O}(1)$

# Big- $\mathcal{O}$ notation (determining asymptotic complexity)

- ③ **If-Else condition:** IF  $C$  THEN  $A1$  ELSE  $A2$  needs time:  
 $T_C + \max(T_{O1}, T_{O2})$

## Example

```
1: read( $x$ )
2: if  $x \bmod 2 = 0$  then
3:    $x := x + 1$ 
4:   print("Even")
5: else
6:   print("Odd")
7: end if
```

Asymptotic TC:  $\mathcal{O}(1) + \mathcal{O}(1) + \max(\mathcal{O}(1) + \mathcal{O}(1), \mathcal{O}(1)) \in \mathcal{O}(1)$



# Big- $\mathcal{O}$ notation (determining asymptotic complexity)

- ④ **For loop:** the time complexity is the number of iterations multiplied with the time complexity of the *body loop* (i.e. *loop statements*)

## Example (Single for loop)

```
1: for  $i = 1$  to  $n$  do  
2:   sum := sum + a[1]  
3: end for
```

Asymptotic TC:  $n \cdot \mathcal{O}(1) = \mathcal{O}(n)$

# Big- $\mathcal{O}$ notation (determining asymptotic complexity)

## Example (Two nested for loops with one instruction)

```
1: for  $i = 1$  to  $n$  do  
2:   for  $j = 1$  to  $n$  do  
3:      $a[i, j] := i + j$   
4:   end for  
5: end for
```

Asymptotic TC:  $n \cdot \mathcal{O}(n) = \mathcal{O}(n^2)$

# Big- $\mathcal{O}$ notation (determining asymptotic complexity)

## Example (Two nested for loops with two instructions)

```
1: for  $i = 1$  to  $n$  do  
2:   for  $j = 1$  to  $i$  do  
3:      $a := a + 1$   
4:      $b := b - 1$   
5:   end for  
6: end for
```

The outer loop is executed  $n$  times, and the inner loop is executed  $i$  times for each  $j$ . The number of iterations:  $1 + 2 + \dots + n = \frac{n(n+1)}{2} \in \mathcal{O}(n^2)$ .

The body loop needs  $\mathcal{O}(1)$ -time.

Asymptotic time complexity:  $\mathcal{O}(n^2)$

# Big- $\mathcal{O}$ notation (determining asymptotic complexity)

- 5 **While loop:** WHILE C DO A; and REPEAT A UNTIL C.

Time complexity = # iterations  $\times T_{\text{body}}$

Example (Single loop with  $n - 1$  iterations)

```
1:  $i := 2$ 
2: while  $i \leq n$  do
3:   sum := sum +  $a[i]$ 
4:    $i := i + 1$ 
5: end while
```

Asymptotic TC:

$$\mathcal{O}(1) + (n - 1)(\mathcal{O}(1) + \mathcal{O}(1) + \mathcal{O}(1)) = \mathcal{O}(1) + \mathcal{O}(n - 1) \in \mathcal{O}(n)$$

# Big- $\mathcal{O}$ notation (determining asymptotic complexity)

## Example (Infinite loop)

```
1:  $x := 0$   
2: while  $x < 5$  do  
3:    $x := 1$   
4:    $x := x + 1$   
5: end while
```

In this situation,  $x$  will never be greater than 5, since at the start of the while loop,  $x$  is given the value of 1, thus, the loop will always end in 2 and the loop will never break.

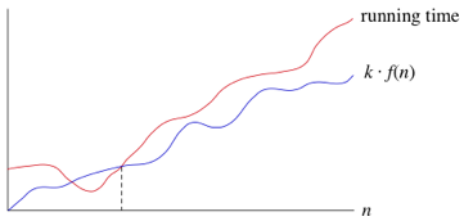
# Big- $\Omega$ notation (asymptotic lower-bound)

We can also say that an algorithm takes *at least a certain amount of time*, without providing an upper bound.

## Big-Omega ( $\Omega(\cdot)$ ) notation

### Definition

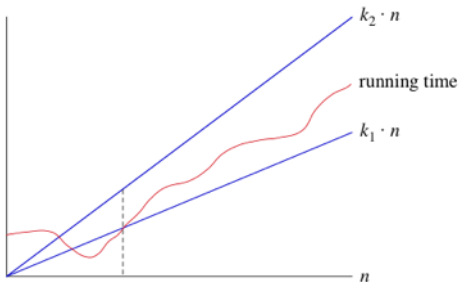
$g(n) \in \Omega(f(n))$  if  $\exists k > 0$  and  $n_0$  s.t.  $g(n) \geq k \cdot f(n)$ ,  $\forall n \geq n_0$ .



# Big- $\Theta$ notation (asymptotically tight-bound)

## Definition

$g(n) \in \Theta(f(n))$  if  $\exists k_1, k_2 > 0$  and  $n_0$  s.t.  
 $k_1 \cdot f(n) \leq g(n) \leq k_2 \cdot f(n), \forall n \geq n_0$ .



# QUIZ



## Exc 1: Growth of function in Big- $\mathcal{O}$

Which kind of growth best characterizes each of these functions?

	Constant	Linear	Polynomial	Exponential
$(3/2)^n$				
1				
$(3/2)^n$				
$2n^3$				
$2^n$				
$3n^2$				
1000				
$3n$				

## Exc 1: Growth of function in Big- $\mathcal{O}$

Which kind of growth best characterizes each of these functions?

	Constant	Linear	Polynomial	Exponential
$(3/2)^n$				✓
1	✓			
$(3/2)^n$		✓		
$2n^3$			✓	
$2^n$				✓
$3n^2$			✓	
1000	✓			
$3n$		✓		

## Exc 2: Comparing function growth

Match each function with an equivalent function that satisfies  $g(n) = \Theta(f(n))$ .

$g(n)$	$f(n)$
$n + 30$	$n^2 + 3n$
$n^2 + 2n - 10$	$n^4$
$n^3 * 3n$	$\log_2 2x$
$\log_2 x$	$3n - 1$

## Exc 2: Comparing function growth

Recall that  $g(n) \in \Theta(f(n))$  if  $\exists k_1, k_2 > 0$  s.t. for all sufficiently large  $n$ , we have

$$k_1 \cdot f(n) \leq g(n) \leq k_2 \cdot f(n)$$

We drop the constants and lower order terms (i.e. only keep the most significant term).

$g(n)$	simplified	$f(n)$	simplified
$n + 30$	$n$	$n^2 + 3n$	$n^2$
$n^2 + 2n - 10$	$n^2$	$n^4$	$n^4$
$n^3 * 3n$	$n^4$	$\log_2 2x$	$\log x$
$\log_2 x$	$\log x$	$3n - 1$	$n$

Two functions match if the corresponding simplified functions are equal.

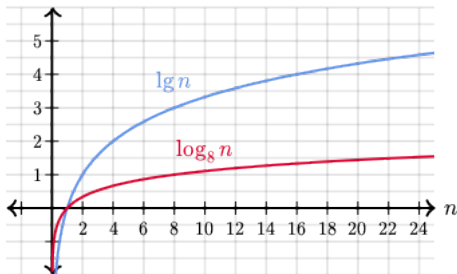
## Exc 3: Asymptotic notation

For the functions  $\log_2 n$  and  $\log_8 n$ , what is the asymptotic relationship between these functions?

- $\log_2 n$  is in  $\mathcal{O}(\log_8 n)$
- $\log_2 n$  is in  $\Omega(\log_8 n)$
- $\log_2 n$  is in  $\Theta(\log_8 n)$

## Exc 3: Asymptotic notation

Both  $\log_2 n$  and  $\log_8 n$  are functions with logarithmic growth, with their base as the only difference.



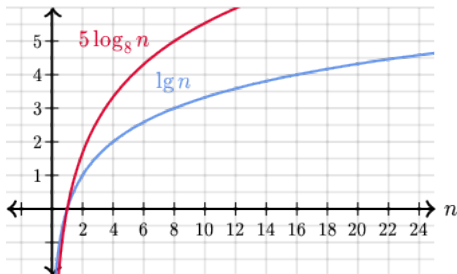
## Exc 3: Asymptotic notation

- Is  $\log_2 n$  in  $\mathcal{O}(\log_8 n)$ ?

Recall that  $\log_a n = \frac{\log_b n}{\log_b a}$ .

So,  $\log_8 n = \frac{\log_2 n}{\log_2 8} = \frac{\log_2 n}{3} = \frac{1}{3} \cdot \log_2 n$ .

We can take  $k = 5$ , so that:  $\log_2 n \leq 5 \log_8 n$ .



## Exc 3: Asymptotic notation

- Is  $\log_2 n$  in  $\Omega(\log_8 n)$ ?

Since  $\log_8 n = \frac{1}{3} \cdot \log_2 n$ , then  $\log_2 n \geq \log_8 n$  for all  $n \geq 1$ .

So,  $\log_2 n \in \Omega(\log_8 n)$



## Exc 3: Asymptotic notation

- Is  $\log_2 n$  in  $\Theta(\log_8 n)$ ?

Clearly,  $\log_8 n \leq \log_2 n \leq 5 \cdot \log_8 n$  for all  $n > 1$ .

So,  $\log_2 n \in \Theta(\log_8 n)$ .

