

# CS 240 – Data Structures and Data Management

## Module 1: Introduction and Asymptotic Analysis

A. Storjohann

Based on lecture notes by many previous cs240 instructors

David R. Cheriton School of Computer Science, University of Waterloo

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References: Goodrich & Tamassia 1.1, 1.2, 1.3  
Sedgewick 8.2, 8.3

# Outline

## 1 Introduction and Asymptotic Analysis

- CS240 Overview
- Algorithm Design
- Analysis of Algorithms I
- Asymptotic Notation
- Analysis of Algorithms II
- Example: Analysis of MergeSort
- Helpful Formulas

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# Course Objectives: What is this course about?

- When first learning to program, we emphasize *correctness*: does your program output the expected results?
- Starting with this course, we will also be concerned with *efficiency*: is your program using the computer's resources (typically processor time) efficiently?
- We will study efficient methods of *storing*, *accessing*, and performing *operations* on large collections of data.
- Typical operations include: *inserting* new data items, *deleting* data items, *searching* for specific data items, *sorting*.
- **Motivating examples:** Digital Music Collection, English Dictionary

# Course Objectives: What is this course about?

- We will consider various **abstract data types** (ADTs) and how to implement them efficiently using appropriate **data structures**.
- There is a strong emphasis on mathematical analysis in the course.
- Algorithms are presented using pseudocode and analyzed using order notation (big-Oh, etc.).

# Course Topics

- big-Oh analysis
- priority queues and heaps
- sorting, selection
- binary search trees, AVL trees, B-trees
- skip lists
- hashing
- quadtrees, kd-trees
- range search
- tries
- string matching
- data compression

# CS Background

Topics covered in previous courses with relevant sections in [Sedgewick]:

- arrays, linked lists (Sec. 3.2–3.4)
- strings (Sec. 3.6)
- stacks, queues (Sec. 4.2–4.6)
- abstract data types (Sec. 4-intro, 4.1, 4.8–4.9)
- recursive algorithms (5.1)
- binary trees (5.4–5.7)
- sorting (6.1–6.4)
- binary search (12.4)
- binary search trees (12.5)
- probability and expectations (Goodrich & Tamassia, Section 1.3.4)

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# Problems (terminology)

First, we must introduce terminology so that we can precisely characterize what we mean by efficiency.

**Problem:** Given a problem instance, carry out a particular computational task.

**Problem Instance:** *Input* for the specified problem.

**Problem Solution:** *Output* (correct answer) for the specified problem instance.

**Size of a problem instance:**  $Size(I)$  is a positive integer which is a measure of the size of the instance  $I$ .

Example: Sorting problem

# Algorithms and Programs

**Algorithm:** An algorithm is a *step-by-step process* (e.g., described in pseudocode) for carrying out a series of computations, given an arbitrary problem instance  $I$ .

**Algorithm solving a problem:** An Algorithm  $A$  *solves* a problem  $\Pi$  if, for every instance  $I$  of  $\Pi$ ,  $A$  finds (computes) a valid solution for the instance  $I$  in finite time.

**Program:** A program is an *implementation* of an algorithm using a specified computer language.

In this course, our emphasis is on algorithms (as opposed to programs or programming).

# Algorithms and Programs

**Pseudocode:** a method of communicating an algorithm to another person.

In contrast, a program is a method of communicating an algorithm to a computer.

## Pseudocode

- omits obvious details, e.g. variable declarations,
- has limited if any error detection,
- sometimes uses English descriptions,
- sometimes uses mathematical notation.

# Algorithms and Programs

For a problem  $\Pi$ , we can have several algorithms.

For an algorithm  $\mathcal{A}$  solving  $\Pi$ , we can have several programs (implementations).

Algorithms in practice: Given a problem  $\Pi$

- ① Design an algorithm  $\mathcal{A}$  that solves  $\Pi$ . → **Algorithm Design**
- ② Assess *correctness* and *efficiency* of  $\mathcal{A}$ . → **Algorithm Analysis**
- ③ If acceptable (correct and efficient), implement  $\mathcal{A}$ .

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# Efficiency of Algorithms/Programs

- How do we decide which algorithm or program is the most efficient solution to a given problem?
- In this course, we are primarily concerned with the *amount of time* a program takes to run.  
→ **Running Time**
- We also may be interested in the *amount of memory* the program requires.  
→ **Space**
- The amount of time and/or memory required by a program will depend on *Size( $I$ )*, the size of the given problem instance  $I$ .

# Running Time of Algorithms/Programs

First Option: *experimental studies*

- Write a program implementing the algorithm.
- Run the program with inputs of varying size and composition.
- Use a method like `clock()` (from `time.h`) to get an accurate measure of the actual running time.
- Plot/compare the results.

# Running Time of Algorithms/Programs

## Shortcomings of experimental studies

- Implementation may be complicated/costly.
- Timings are affected by many factors: *hardware* (processor, memory), *software environment* (OS, compiler, programming language), and human factors (programmer).
- We cannot test all inputs; what are good *sample inputs*?
- We cannot easily compare two algorithms/programs.

## We want a framework that:

- Does not require implementing the algorithm.
- Is independent of the hardware/software environment.
- Takes into account all input instances.

## We need some *simplifications*.



# Overview of Algorithm Analysis

We will develop several aspects of algorithm analysis in the next slides.

- Algorithms are presented in structured high-level *pseudocode* which is language-independent.
- Analysis of algorithms is based on an *idealized computer model*.
- The efficiency of an algorithm (with respect to time) is measured in terms of its *growth rate* (this is called the *complexity* of the algorithm).

# Running Time Simplifications

## Overcome dependency on hardware/software

- Express algorithms using *pseudo-code*
- Instead of time, count the number of *primitive operations*
- Implicit assumption: primitive operations have fairly similar, though different, running time on different systems

## Random Access Machine (RAM) Model:

- The *random access machine* has a set of memory cells, each of which stores one item (word) of data.
- Any *access to a memory location* takes constant time.
- Any *primitive operation* takes constant time.
- The *running time* of a program can be computed to be the number of memory accesses plus the number of primitive operations.

This is an idealized model, so these assumptions may not be valid for a “real” computer.

# Running Time Simplifications

## Simplify Comparisons

- Example: Compare  $100n$  with  $10n^2$
- Idea: Use *order notation*
- Informally: ignore constants and lower order terms

We will simplify our analysis by considering the behaviour of algorithms for large inputs sizes.

# Outline

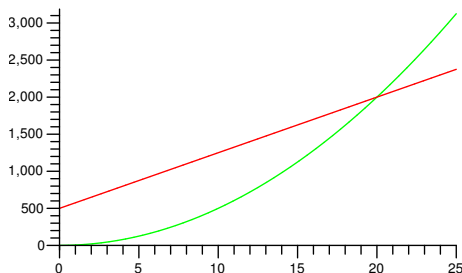
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# Order Notation

**$O$ -notation:**  $f(n) \in O(g(n))$  if there exist constants  $c > 0$  and  $n_0 > 0$  such that  $|f(n)| \leq c |g(n)|$  for all  $n \geq n_0$ .

Example:  $f(n) = 75n + 500$  and  $g(n) = 5n^2$  (e.g.  $c = 1, n_0 = 20$ )



**Note:** The absolute value signs in the definition are irrelevant for analysis of run-time or space, but are useful in other applications of asymptotic notation.

## Example of Order Notation

In order to prove that  $2n^2 + 3n + 11 \in O(n^2)$  from first principles, we need to find  $c$  and  $n_0$  such that the following condition is satisfied:

$$0 \leq 2n^2 + 3n + 11 \leq c n^2 \text{ for all } n \geq n_0.$$

note that not all choices of  $c$  and  $n_0$  will work.

# Asymptotic Lower Bound

- We have  $2n^2 + 3n + 11 \in O(n^2)$ .
- But we also have  $2n^2 + 3n + 11 \in O(n^{10})$ .
- We want a **tight** asymptotic bound.

**$\Omega$ -notation:**  $f(n) \in \Omega(g(n))$  if there exist constants  $c > 0$  and  $n_0 > 0$  such that  $c |g(n)| \leq |f(n)|$  for all  $n \geq n_0$ .

**$\Theta$ -notation:**  $f(n) \in \Theta(g(n))$  if there exist constants  $c_1, c_2 > 0$  and  $n_0 > 0$  such that  $c_1 |g(n)| \leq |f(n)| \leq c_2 |g(n)|$  for all  $n \geq n_0$ .

$$f(n) \in \Theta(g(n)) \Leftrightarrow f(n) \in O(g(n)) \text{ and } f(n) \in \Omega(g(n))$$

## Example of Order Notation

Prove that  $\frac{1}{2}n^2 - 5n \in \Omega(n^2)$  from first principles.



# Strictly smaller/larger asymptotic bounds

- We have  $f(n) = 2n^2 + 3n + 11 \in \Theta(n^2)$ .
- How to express that  $f(n)$  is **asymptotically strictly smaller** than  $n^3$ ?

**$o$ -notation:**  $f(n) \in o(g(n))$  if for all constants  $c > 0$ , there exists a constant  $n_0 > 0$  such that  $|f(n)| < c |g(n)|$  for all  $n \geq n_0$ .

**$\omega$ -notation:**  $f(n) \in \omega(g(n))$  if for all constants  $c > 0$ , there exists a constant  $n_0 > 0$  such that  $0 \leq c |g(n)| < |f(n)|$  for all  $n \geq n_0$ .

- Rarely proved from first principles.

# Relationships between Order Notations

- $f(n) \in \Theta(g(n)) \Leftrightarrow g(n) \in \Theta(f(n))$
  - $f(n) \in O(g(n)) \Leftrightarrow g(n) \in \Omega(f(n))$
  - $f(n) \in o(g(n)) \Leftrightarrow g(n) \in \omega(f(n))$
- 
- $f(n) \in o(g(n)) \Rightarrow f(n) \in O(g(n))$
  - $f(n) \in o(g(n)) \Rightarrow f(n) \notin \Omega(g(n))$
  - $f(n) \in \omega(g(n)) \Rightarrow f(n) \in \Omega(g(n))$
  - $f(n) \in \omega(g(n)) \Rightarrow f(n) \notin O(g(n))$

# Algebra of Order Notations

**“Identity” rule:**  $f(n) \in \Theta(f(n))$

**“Maximum” rules:** Suppose that  $f(n) > 0$  and  $g(n) > 0$  for all  $n \geq n_0$ .  
Then:

- $O(f(n) + g(n)) = O(\max\{f(n), g(n)\})$
- $\Omega(f(n) + g(n)) = \Omega(\max\{f(n), g(n)\})$

**Transitivity:**

- If  $f(n) \in O(g(n))$  and  $g(n) \in O(h(n))$  then  $f(n) \in O(h(n))$ .
- If  $f(n) \in \Omega(g(n))$  and  $g(n) \in \Omega(h(n))$  then  $f(n) \in \Omega(h(n))$ .

# Techniques for Order Notation

Suppose that  $f(n) > 0$  and  $g(n) > 0$  for all  $n \geq n_0$ . Suppose that

$$L = \lim_{n \rightarrow \infty} \frac{f(n)}{g(n)}.$$

Then

$$f(n) \in \begin{cases} o(g(n)) & \text{if } L = 0 \\ \Theta(g(n)) & \text{if } 0 < L < \infty \\ \omega(g(n)) & \text{if } L = \infty. \end{cases}$$

The required limit can often be computed using *l'Hôpital's rule*. Note that this result gives *sufficient* (but not necessary) conditions for the stated conclusions to hold.

# Example 1

Let  $f(n)$  be a polynomial of degree  $d \geq 0$ :

$$f(n) = c_d n^d + c_{d-1} n^{d-1} + \dots + c_1 n + c_0$$

for some  $c_d > 0$ .

Then  $f(n) \in \Theta(n^d)$ :

## Example 2

Prove that  $n(2 + \sin n\pi/2)$  is  $\Theta(n)$ . Note that  $\lim_{n \rightarrow \infty} (2 + \sin n\pi/2)$  does not exist.

# Growth Rates

- If  $f(n) \in \Theta(g(n))$ , then the *growth rates* of  $f(n)$  and  $g(n)$  are the *same*.
- If  $f(n) \in o(g(n))$ , then we say that the growth rate of  $f(n)$  is *less than* the growth rate of  $g(n)$ .
- If  $f(n) \in \omega(g(n))$ , then we say that the growth rate of  $f(n)$  is *greater than* the growth rate of  $g(n)$ .
- Typically,  $f(n)$  may be “complicated” and  $g(n)$  is chosen to be a very simple function.

## Example 3

Compare the growth rates of  $\log n$  and  $n$ .

Now compare the growth rates of  $(\log n)^c$  and  $n^d$  (where  $c > 0$  and  $d > 0$  are arbitrary numbers).



# Common Growth Rates

Commonly encountered growth rates in analysis of algorithms include the following (in increasing order of growth rate):

- $\Theta(1)$  (*constant complexity*),
- $\Theta(\log n)$  (*logarithmic complexity*),
- $\Theta(n)$  (*linear complexity*),
- $\Theta(n \log n)$  (*linearithmic*),
- $\Theta(n \log^k n)$ , for some constant  $k$  (*quasi-linear*),
- $\Theta(n^2)$  (*quadratic complexity*),
- $\Theta(n^3)$  (*cubic complexity*),
- $\Theta(2^n)$  (*exponential complexity*).

# How Growth Rates Affect Running Time

It is interesting to see how the running time is affected when the size of the problem instance **doubles** (i.e.,  $n \rightarrow 2n$ ).

- constant complexity:  $T(n) = c$   $\rightsquigarrow T(2n) = c.$
- logarithmic complexity:  $T(n) = c \log n$   $\rightsquigarrow T(2n) = T(n) + c.$
- linear complexity:  $T(n) = cn$   $\rightsquigarrow T(2n) = 2T(n).$
- linearithmic  $\Theta(n \log n)$ :  $T(n) = cn \log n$   $\rightsquigarrow T(2n) = 2T(n) + 2cn.$
- quadratic complexity:  $T(n) = cn^2$   $\rightsquigarrow T(2n) = 4T(n).$
- cubic complexity:  $T(n) = cn^3$   $\rightsquigarrow T(2n) = 8T(n).$
- exponential complexity:  $T(n) = c2^n$   $\rightsquigarrow T(2n) = (T(n))^2/c.$

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# Techniques for Algorithm Analysis

- Goal: Use asymptotic notation to simplify run-time analysis.
- Running time of an algorithm depends on the *input size*  $n$ .

```
Test1( $n$ )  
1.   $sum \leftarrow 0$   
2.  for  $i \leftarrow 1$  to  $n$  do  
3.      for  $j \leftarrow i$  to  $n$  do  
4.           $sum \leftarrow sum + (i - j)^2$   
5.  return  $sum$ 
```

- Identify *elementary operations* that require  $\Theta(1)$  time.
- The complexity of a loop is expressed as the *sum* of the complexities of each iteration of the loop.
- Nested loops: start with the innermost loop and proceed outwards. This gives *nested summations*.

# Techniques for Algorithm Analysis

Two general strategies are as follows.

- Use  $\Theta$ -bounds *throughout the analysis* and obtain a  $\Theta$ -bound for the complexity of the algorithm.
- Prove a  $O$ -bound and a *matching*  $\Omega$ -bound *separately*.  
Use upper bounds (for  $O$ -bounds) and lower bounds (for  $\Omega$ -bound) early and frequently.  
This may be easier because upper/lower bounds are easier to sum.

```
Test2(A, n)
1.   max ← 0
2.   for i ← 1 to n do
3.       for j ← i to n do
4.           sum ← 0
5.           for k ← i to j do
6.               sum ← A[k]
7.   return max
```

# Complexity of Algorithms

- Algorithm can have different running times on two instances of the same size.

```
Test3( $A, n$ )  
 $A$ : array of size  $n$   
1.   for  $i \leftarrow 1$  to  $n - 1$  do  
2.        $j \leftarrow i$   
3.       while  $j > 0$  and  $A[j] > A[j - 1]$  do  
4.           swap  $A[j]$  and  $A[j - 1]$   
5.            $j \leftarrow j - 1$ 
```

Let  $T_A(I)$  denote the running time of an algorithm  $A$  on instance  $I$ .

**Worst-case complexity of an algorithm:** take the worst  $I$

**Average-case complexity of an algorithm:** average over  $I$

# Complexity of Algorithms

**Worst-case complexity of an algorithm:** The worst-case running time of an algorithm  $A$  is a function  $f : \mathbb{Z}^+ \rightarrow \mathbb{R}$  mapping  $n$  (the input size) to the *longest* running time for any input instance of size  $n$ :

$$T_A(n) = \max\{T_A(I) : \text{Size}(I) = n\}.$$

**Average-case complexity of an algorithm:** The average-case running time of an algorithm  $A$  is a function  $f : \mathbb{Z}^+ \rightarrow \mathbb{R}$  mapping  $n$  (the input size) to the *average* running time of  $A$  over all instances of size  $n$ :

$$T_A^{avg}(n) = \frac{1}{|\{I : \text{Size}(I) = n\}|} \sum_{\{I : \text{Size}(I) = n\}} T_A(I).$$

# O-notation and Complexity of Algorithms

- It is important not to try and make *comparisons* between algorithms using O-notation.
- For example, suppose algorithm  $A_1$  and  $A_2$  both solve the same problem,  $A_1$  has worst-case run-time  $O(n^3)$  and  $A_2$  has worst-case run-time  $O(n^2)$ .
- Observe that we *cannot* conclude that  $A_2$  is more efficient than  $A_1$  for all input!
  - ① The worst-case run-time may only be achieved on some instances.
  - ② O-notation is an upper bound.  $A_1$  may well have worst-case run-time  $O(n)$ . If we want to be able to compare algorithms, we should always use  $\Theta$ -notation.



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# Design of MergeSort

**Input:** Array  $A$  of  $n$  integers

- *Step 1:* We split  $A$  into two subarrays:  $A_L$  consists of the first  $\lceil \frac{n}{2} \rceil$  elements in  $A$  and  $A_R$  consists of the last  $\lfloor \frac{n}{2} \rfloor$  elements in  $A$ .
- *Step 2:* *Recursively* run *MergeSort* on  $A_L$  and  $A_R$ .
- *Step 3:* After  $A_L$  and  $A_R$  have been sorted, use a function *Merge* to merge them into a single sorted array.

# MergeSort

To avoid copying sub-arrays, the recursion uses parameters that indicate the range of the array that needs to be sorted.

```
MergeSort( $A, \ell \leftarrow 0, r \leftarrow n - 1$ )  
A: array of size  $n$ ,  $0 \leq \ell \leq r \leq n - 1$   
1.   if ( $r \leq \ell$ ) then  
2.       return  
3.   else  
4.        $m = (r + \ell) / 2$   
5.       MergeSort( $A, \ell, m$ )  
6.       MergeSort( $A, m + 1, r$ )  
7.       Merge( $A, \ell, m, r$ )
```

# Merge

*Merge*( $A, \ell, m, r$ )

$A[0..n-1]$  is an array,  $A[\ell..m]$  is sorted,  $A[m+1..r]$  is sorted

1. initialize auxiliary array  $S[0..n-1]$
2. copy  $A[\ell..r]$  into  $S[\ell..r]$
3.  $\text{int } i_L \leftarrow \ell; \text{int } i_R \leftarrow m+1;$
4. **for** ( $k \leftarrow \ell; k \leq r; k++$ ) **do**
5.     **if** ( $i_L > m$ )  $A[k] \leftarrow S[i_R++]$
6.     **elseif** ( $i_R > r$ )  $A[k] \leftarrow S[i_L++]$
7.     **elseif** ( $S[i_L] \leq S[i_R]$ )  $A[k] \leftarrow S[i_L++]$
8.     **else**  $A[k] \leftarrow S[i_R++]$

Sedgewick's code is slightly more complicated to avoid having to check whether  $i_R$  and  $i_L$  are out-of-boundary.

*Merge* takes time  $\Theta(r - \ell + 1)$ , i.e.,  $\Theta(n)$  time for merging  $n$  elements.

# Analysis of MergeSort

Let  $T(n)$  denote the time to run *MergeSort* on an array of length  $n$ .

- Step 1 takes time  $\Theta(n)$
- Step 2 takes time  $T(\lceil \frac{n}{2} \rceil) + T(\lfloor \frac{n}{2} \rfloor)$
- Step 3 takes time  $\Theta(n)$

The *recurrence relation* for  $T(n)$  is as follows:

$$T(n) = \begin{cases} T(\lceil \frac{n}{2} \rceil) + T(\lfloor \frac{n}{2} \rfloor) + \Theta(n) & \text{if } n > 1 \\ \Theta(1) & \text{if } n = 1. \end{cases}$$

It suffices to consider the following *exact recurrence*, with constant factor  $c$  replacing  $\Theta$ 's:

$$T(n) = \begin{cases} T(\lceil \frac{n}{2} \rceil) + T(\lfloor \frac{n}{2} \rfloor) + cn & \text{if } n > 1 \\ c & \text{if } n = 1. \end{cases}$$

# Analysis of MergeSort

- The following is the corresponding *sloppy recurrence* (it has floors and ceilings removed):

$$T(n) = \begin{cases} 2 T(\frac{n}{2}) + cn & \text{if } n > 1 \\ c & \text{if } n = 1. \end{cases}$$

- The exact and sloppy recurrences are *identical* when  $n$  is a power of 2.
- The recurrence can easily be solved by various methods when  $n = 2^j$ . The solution has growth rate  $T(n) \in \Theta(n \log n)$ .
- It is possible to show that  $T(n) \in \Theta(n \log n)$  *for all*  $n$  by analyzing the exact recurrence.

# Some Recurrence Relations

Recursion	resolves to	example
$T(n) = T(n/2) + \Theta(1)$	$T(n) \in \Theta(\log n)$	Binary search
$T(n) = 2T(n/2) + \Theta(n)$	$T(n) \in \Theta(n \log n)$	Mergesort
$T(n) = 2T(n/2) + \Theta(\log n)$	$T(n) \in \Theta(n)$	Heapify ( $\rightarrow$ later)
$T(n) = T(cn) + \Theta(n)$ for some $0 < c < 1$	$T(n) \in \Theta(n)$	Selection ( $\rightarrow$ later)
$T(n) = 2T(n/4) + \Theta(1)$	$T(n) \in \Theta(\sqrt{n})$	Range Search ( $\rightarrow$ later)
$T(n) = T(\sqrt{n}) + \Theta(1)$	$T(n) \in \Theta(\log \log n)$	Interpolation Search ( $\rightarrow$ later)

- Once you know the result, it is (usually) easy to prove by induction.
- Many more recursions, and some methods to find the result, in cs341.

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# Order Notation Summary

**$O$ -notation:**  $f(n) \in O(g(n))$  if there exist constants  $c > 0$  and  $n_0 > 0$  such that  $|f(n)| \leq c |g(n)|$  for all  $n \geq n_0$ .

**$\Omega$ -notation:**  $f(n) \in \Omega(g(n))$  if there exist constants  $c > 0$  and  $n_0 > 0$  such that  $c |g(n)| \leq |f(n)|$  for all  $n \geq n_0$ .

**$\Theta$ -notation:**  $f(n) \in \Theta(g(n))$  if there exist constants  $c_1, c_2 > 0$  and  $n_0 > 0$  such that  $c_1 |g(n)| \leq |f(n)| \leq c_2 |g(n)|$  for all  $n \geq n_0$ .

**$o$ -notation:**  $f(n) \in o(g(n))$  if for all constants  $c > 0$ , there exists a constant  $n_0 > 0$  such that  $|f(n)| < c |g(n)|$  for all  $n \geq n_0$ .

**$\omega$ -notation:**  $f(n) \in \omega(g(n))$  if for all constants  $c > 0$ , there exists a constant  $n_0 > 0$  such that  $c |g(n)| < |f(n)|$  for all  $n \geq n_0$ .

# Useful Sums

## Arithmetic sequence:

$$\sum_{i=0}^{n-1} i = ??? \qquad \sum_{i=0}^{n-1} (a + di) = na + \frac{dn(n-1)}{2} \in \Theta(n^2) \quad \text{if } d \neq 0.$$

## Geometric sequence:

$$\sum_{i=0}^{n-1} r^i = ??? \qquad \sum_{i=0}^{n-1} a r^i = \begin{cases} a \frac{r^n - 1}{r - 1} & \in \Theta(r^n) \quad \text{if } r > 1 \\ na & \in \Theta(n) \quad \text{if } r = 1 \\ a \frac{1 - r^n}{1 - r} & \in \Theta(1) \quad \text{if } 0 < r < 1. \end{cases}$$

## Harmonic sequence:

$$\sum_{i=1}^n \frac{1}{i} = ??? \qquad H_n := \sum_{i=1}^n \frac{1}{i} = \ln n + \gamma + o(1) \in \Theta(\log n)$$

## A few more:

$$\sum_{i=1}^n \frac{1}{i^2} = ??? \qquad \sum_{i=1}^n \frac{1}{i^2} = \frac{\pi^2}{6} \in \Theta(1)$$

$$\sum_{i=1}^n i^k = ??? \qquad \sum_{i=1}^n i^k \in \Theta(n^{k+1}) \quad \text{for } k \geq 0$$

# Useful Math Facts

## Logarithms:

- $c = \log_b(a)$  means  $b^c = a$ . E.g.  $n = 2^{\log n}$ .
- $\log(a)$  usually means  $\log_2(a)$  in this course
- $\log(a \cdot c) = \log(a) + \log(c)$ ,  $\log(a^c) = c \log(a)$ ,
- $\log_b(a) = \frac{\log_c a}{\log_c b} = \frac{1}{\log_a(b)}$ .
- $a^{\log_b c} = c^{\log_b a}$
- $\ln(x) = \text{natural log} = \log_e(x)$ ,  $\frac{d}{dx} \ln x = \frac{1}{x}$

## Factorial:

- $n! := n(n-1)(n-2) \cdots 2 \cdot 1 = \#$  ways to permute  $n$  elements
- $\log(n!) = \log n + \log(n-1) + \cdots + \log 2 + \log 1 \in \Theta(n \log n)$

## Probability and moments:

- $E[aX] = aE[X]$ ,  $E[X + Y] = E[X] + E[Y]$  (linearity of expectation)