CSE 431/531: Algorithm Analysis and Design (Fall 2022)

Introduction and Syllabus

Lecturer: Shi Li

Department of Computer Science and Engineering
University at Buffalo
Outline

1 Syllabus

2 Introduction
   - What is an Algorithm?
   - Example: Insertion Sort
   - Analysis of Insertion Sort

3 Asymptotic Notations

4 Common Running times
Course Webpage (contains schedule, policies, and slides):
http://www.cse.buffalo.edu/~shil/courses/CSE531/

Please sign up course on Piazza via link on course webpage
- homeworks, solutions, announcements, polls, asking/answering questions
CSE 431/531: Algorithm Analysis and Design

- Time & Location: TuTh, 5:00pm - 6:20pm, Cooke 121
- Instructor:
  - Shi Li, shil@buffalo.edu
- TAs and Graders: TBD
You **should** already have/know:
You should already have/know:

- **Mathematical Background**
- **basic reasoning skills, inductive proofs**
You should already have/know:

- **Mathematical Background**
  - basic reasoning skills, inductive proofs

- **Basic data Structures**
  - linked lists, arrays
  - stacks, queues
You should already have/know:

- **Mathematical Background**
  - basic reasoning skills, inductive proofs

- **Basic data Structures**
  - linked lists, arrays
  - stacks, queues

- **Some Programming Experience**
  - Python, C, C++ or Java
You Will Learn

- Classic algorithms for classic problems
- Sorting, shortest paths, minimum spanning tree, ...
You Will Learn

- Classic algorithms for classic problems
  - Sorting, shortest paths, minimum spanning tree, · · ·

- How to analyze algorithms
  - Correctness
  - Running time (efficiency)
You Will Learn

- Classic algorithms for classic problems
  - Sorting, shortest paths, minimum spanning tree, · · ·
- How to analyze algorithms
  - Correctness
  - Running time (efficiency)
- Meta techniques to design algorithms
  - Greedy algorithms
  - Divide and conquer
  - Dynamic programming
  - · · ·
You Will Learn

- Classic algorithms for classic problems
  - Sorting, shortest paths, minimum spanning tree, ···
- How to analyze algorithms
  - Correctness
  - Running time (efficiency)
- Meta techniques to design algorithms
  - Greedy algorithms
  - Divide and conquer
  - Dynamic programming
  - ···
- NP-completeness
### Tentative Schedule

**80 Minutes/Lecture × 29 Lectures**

<table>
<thead>
<tr>
<th>Course</th>
<th>Lectures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>3 lectures</td>
</tr>
<tr>
<td>Graph Basics</td>
<td>2 lectures</td>
</tr>
<tr>
<td>Greedy Algorithms</td>
<td>5 lectures</td>
</tr>
<tr>
<td>Divide and Conquer</td>
<td>4 lectures</td>
</tr>
<tr>
<td>Dynamic Programming</td>
<td>5 lectures</td>
</tr>
<tr>
<td>Graph Algorithms</td>
<td>5 lectures</td>
</tr>
<tr>
<td>NP-Completeness</td>
<td>4 lectures</td>
</tr>
<tr>
<td>Final Review</td>
<td>1 lectures</td>
</tr>
</tbody>
</table>
Textbook (Highly Recommended):
- **Algorithm Design**, 1st Edition, by *Jon Kleinberg and Eva Tardos*

Other Reference Books
Highly recommended: read the correspondent sections from the textbook (or reference book) before classes

Sections for each lecture can be found on the course webpage.

Slides are posted on course webpage. They may get updated before the classes start.

In last lecture of a major topic (Greedy Algorithms, Divide and Conquer, Dynamic Programming, Graph Algorithms), I will discuss exercise problems, which will be posted on the course webpage before class.
Grading

- 10% for participation
  - In-class quizzes will be given randomly.
- 40% for theory homeworks
  - 8 points × 5 theory homeworks
- 20% for programming problems
  - 10 points × 2 programming assignments
- 30% for final exam
For Homeworks, You Are Allowed to

- Use course materials (textbook, reference books, lecture notes, etc)
- Post questions on Piazza
- Ask me or TAs for hints
- Collaborate with classmates
  - Think about each problem for enough time before discussions
  - Must write down solutions on your own, in your own words
  - Write down names of students you collaborated with
For Homeworks, You Are Not Allowed to

- Use external resources
  - Can’t Google or ask questions online for solutions
  - Can’t read posted solutions from other algorithm course webpages
- Copy solutions from other students
For Programming Problems

- Need to implement the algorithms by yourself
- Can not copy codes from others or the Internet
- We use Moss (https://theory.stanford.edu/~aiken/moss/) to detect similarity of programs
Late Policy

- You have 1 “late credit”, using it allows you to submit an assignment solution / project for three days. It can not be split across different assignments.
- With no special reasons, no other late submissions will be accepted.
Final Exam will be closed-book

Academic Integrity (AI) Policy for the Course

- minor violation:
  - 0 score for the involved homework/prog. assignment, and
  - 1-letter grade down

- 2 minor violations = 1 major violation
  - failure for the course
  - case will be reported to the department and university
  - further sanctions may include a dishonesty mark on transcript or expulsion from university
Final Exam will be closed-book

Academic Integrity (AI) Policy for the Course

- minor violation:
  - 0 score for the involved homework/prog. assignment, and
  - 1-letter grade down
- 2 minor violations = 1 major violation
  - failure for the course
  - case will be reported to the department and university
  - further sanctions may include a dishonesty mark on transcript or expulsion from university

Questions?
Outline

1. Syllabus

2. Introduction
   - What is an Algorithm?
   - Example: Insertion Sort
   - Analysis of Insertion Sort

3. Asymptotic Notations

4. Common Running times
Outline

1 Syllabus

2 Introduction
   • What is an Algorithm?
   • Example: Insertion Sort
   • Analysis of Insertion Sort

3 Asymptotic Notations

4 Common Running times
What is an Algorithm?

- Donald Knuth: An algorithm is a finite, definite effective procedure, with some input and some output.
What is an Algorithm?

- Donald Knuth: An algorithm is a finite, definite effective procedure, with some input and some output.
- Computational problem: specifies the input/output relationship.
- An algorithm solves a computational problem if it produces the correct output for any given input.
## Greatest Common Divisor

**Input:** two integers $a, b > 0$

**Output:** the greatest common divisor of $a$ and $b$

Example:

Input: 210, 270

Output: 30

Algorithm: Euclidean algorithm

$\text{gcd}(270, 210) = \text{gcd}(210, 270 \mod 210) = \text{gcd}(210, 60)$

$\rightarrow (210, 60)$

$\rightarrow (60, 30)$

$\rightarrow (30, 0)$
Examples

**Greatest Common Divisor**

**Input:** two integers $a, b > 0$

**Output:** the greatest common divisor of $a$ and $b$

Example:
- **Input:** 210, 270
- **Output:** 30
Examples

Greatest Common Divisor

Input: two integers $a, b > 0$

Output: the greatest common divisor of $a$ and $b$

Example:

- Input: 210, 270
- Output: 30

Algorithm: Euclidean algorithm
Examples

Greatest Common Divisor

**Input:** two integers $a, b > 0$

**Output:** the greatest common divisor of $a$ and $b$

Example:

- **Input:** 210, 270
- **Output:** 30

- **Algorithm:** Euclidean algorithm
  
  $\gcd(270, 210) = \gcd(210, 270 \mod 210) = \gcd(210, 60)$
Examples

Greatest Common Divisor

**Input:** two integers \( a, b > 0 \)

**Output:** the greatest common divisor of \( a \) and \( b \)

Example:

- **Input:** 210, 270
- **Output:** 30

**Algorithm:** Euclidean algorithm

- \( \gcd(270, 210) = \gcd(210, 270 \mod 210) = \gcd(210, 60) \)
- \( (270, 210) \rightarrow (210, 60) \rightarrow (60, 30) \rightarrow (30, 0) \)
Sorting

**Input:** sequence of $n$ numbers $(a_1, a_2, \cdots, a_n)$

**Output:** a permutation $(a'_1, a'_2, \cdots, a'_n)$ of the input sequence such that $a'_1 \leq a'_2 \leq \cdots \leq a'_n$
Examples

Sorting

**Input:** sequence of $n$ numbers $(a_1, a_2, \cdots, a_n)$

**Output:** a permutation $(a'_1, a'_2, \cdots, a'_n)$ of the input sequence such that $a'_1 \leq a'_2 \leq \cdots \leq a'_n$

Example:

- **Input:** 53, 12, 35, 21, 59, 15
- **Output:** 12, 15, 21, 35, 53, 59
Examples

**Sorting**

**Input:** sequence of \( n \) numbers \((a_1, a_2, \cdots, a_n)\)

**Output:** a permutation \((a'_1, a'_2, \cdots, a'_n)\) of the input sequence such that \(a'_1 \leq a'_2 \leq \cdots \leq a'_n\)

**Example:**
- **Input:** 53, 12, 35, 21, 59, 15
- **Output:** 12, 15, 21, 35, 53, 59

- Algorithms: insertion sort, merge sort, quicksort, ...
Examples

Shortest Path

**Input:** directed graph $G = (V, E)$, $s, t \in V$

**Output:** a shortest path from $s$ to $t$ in $G$
Examples

Shortest Path

Input: directed graph $G = (V, E), s, t \in V$

Output: a shortest path from $s$ to $t$ in $G$
Examples

**Shortest Path**

**Input**: directed graph \( G = (V, E) \), \( s, t \in V \)

**Output**: a shortest path from \( s \) to \( t \) in \( G \)

![Diagram of a directed graph with nodes labeled 3, s, and t, and edges with weights 3, 4, 5, 1, 16, 1, 2, 4, 10, 10.](image)

Algorithm: Dijkstra's algorithm
Examples

Shortest Path

**Input:** directed graph $G = (V, E), s, t \in V$

**Output:** a shortest path from $s$ to $t$ in $G$

- Algorithm: Dijkstra’s algorithm
Algorithm = Computer Program?

- **Algorithm**: “abstract”, can be specified using computer program, English, pseudo-codes or flow charts.

- **Computer program**: “concrete”, implementation of algorithm, using a particular programming language
Pseudo-Code

Euclidean\((a, b)\)

1: \textbf{while} \(b > 0\) \textbf{do}
2: \quad \(a, b \leftarrow (b, a \mod b)\)
3: \textbf{return} \(a\)

C++ program:

```cpp
int Euclidean(int a, int b){
    int c;
    while (b > 0){
        c = b;
        b = a % b;
        a = c;
    }
    return a;
}
```
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)

- Why is it important to study the running time (efficiency) of an algorithm?

1. feasible vs. infeasible
2. efficient algorithms: less engineering tricks needed, can use languages aiming for easy programming (e.g., python)
3. fundamental
4. it is fun!
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)
- Sometimes: memory usage
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)
- Sometimes: memory usage
- Not covered in the course: engineering side
  - extensibility
  - modularity
  - object-oriented model
  - user-friendliness (e.g., GUI)
  - ...

Why is it important to study the running time (efficiency) of an algorithm?

1. feasible vs. infeasible
2. efficient algorithms: less engineering tricks needed, can use languages aiming for easy programming (e.g., python)
3. fundamental
4. it is fun!
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)
- Sometimes: memory usage
- Not covered in the course: engineering side
  - extensibility
  - modularity
  - object-oriented model
  - user-friendliness (e.g., GUI)
  - ... 

Why is it important to study the running time (efficiency) of an algorithm?
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)
- Sometimes: memory usage
- Not covered in the course: engineering side
  - extensibility
  - modularity
  - object-oriented model
  - user-friendliness (e.g., GUI)
  - ...

Why is it important to study the running time (efficiency) of an algorithm?

feasible vs. infeasible
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)
- Sometimes: memory usage
- Not covered in the course: engineering side
  - extensibility
  - modularity
  - object-oriented model
  - user-friendliness (e.g., GUI)
  - ... 

Why is it important to study the running time (efficiency) of an algorithm?

1. feasible vs. infeasible
2. efficient algorithms: less engineering tricks needed, can use languages aiming for easy programming (e.g., python)
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)
- Sometimes: memory usage
- Not covered in the course: engineering side
  - extensibility
  - modularity
  - object-oriented model
  - user-friendliness (e.g., GUI)
  - ...

Why is it important to study the running time (efficiency) of an algorithm?

1. feasible vs. infeasible
2. efficient algorithms: less engineering tricks needed, can use languages aiming for easy programming (e.g., python)
3. fundamental
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)
- Sometimes: memory usage
- Not covered in the course: engineering side
  - extensibility
  - modularity
  - object-oriented model
  - user-friendliness (e.g., GUI)
  - ...

Why is it important to study the running time (efficiency) of an algorithm?

1. feasible vs. infeasible
2. efficient algorithms: less engineering tricks needed, can use languages aiming for easy programming (e.g., python)
3. fundamental
4. it is fun!
Outline

1. Syllabus

2. Introduction
   - What is an Algorithm?
   - Example: Insertion Sort
   - Analysis of Insertion Sort

3. Asymptotic Notations

4. Common Running times
Sorting Problem

**Input:** sequence of \( n \) numbers \((a_1, a_2, \cdots, a_n)\)

**Output:** a permutation \((a'_1, a'_2, \cdots, a'_n)\) of the input sequence such that \(a'_1 \leq a'_2 \leq \cdots \leq a'_n\)

Example:

- **Input:** 53, 12, 35, 21, 59, 15
- **Output:** 12, 15, 21, 35, 53, 59
Insertion-Sort

- At the end of $j$-th iteration, the first $j$ numbers are sorted.

iteration 1: 53, 12, 35, 21, 59, 15
iteration 2: 12, 53, 35, 21, 59, 15
iteration 3: 12, 35, 53, 21, 59, 15
iteration 4: 12, 21, 35, 53, 59, 15
iteration 5: 12, 21, 35, 53, 59, 15
iteration 6: 12, 15, 21, 35, 53, 59
Example:
- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

insertion-sort($A, n$)

1: for $j \leftarrow 2$ to $n$ do
2: \hspace{1em} $key \leftarrow A[j]$
3: \hspace{1em} $i \leftarrow j - 1$
4: \hspace{1em} while $i > 0$ and $A[i] > key$ do
5: \hspace{2em} $A[i + 1] \leftarrow A[i]$
6: \hspace{1em} $i \leftarrow i - 1$
7: \hspace{1em} $A[i + 1] \leftarrow key$
Example:

- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

**insertion-sort(A, n)**

1: for $j \leftarrow 2$ to $n$ do
2:   $key \leftarrow A[j]$
3:   $i \leftarrow j - 1$
4:   while $i > 0$ and $A[i] > key$ do
5:     $A[i + 1] \leftarrow A[i]$
6:     $i \leftarrow i - 1$
7:   $A[i + 1] \leftarrow key$

- $j = 6$
- $key = 15$

12 21 35 53 59 15

↑

$i$
Example:

- **Input:** 53, 12, 35, 21, 59, 15
- **Output:** 12, 15, 21, 35, 53, 59

**insertion-sort**(A, n)

1: for \( j \leftarrow 2 \) to \( n \) do
2: \( key \leftarrow A[j] \)
3: \( i \leftarrow j - 1 \)
4: while \( i > 0 \) and \( A[i] > key \) do
5: \( A[i + 1] \leftarrow A[i] \)
6: \( i \leftarrow i - 1 \)
7: \( A[i + 1] \leftarrow key \)

- \( j = 6 \)
- \( key = 15 \)

<table>
<thead>
<tr>
<th>12</th>
<th>21</th>
<th>35</th>
<th>53</th>
<th>59</th>
<th>59</th>
</tr>
</thead>
</table>

\( \uparrow i \)
Example:

- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

insertion-sort\((A, n)\)

1: for \(j \leftarrow 2\) to \(n\) do
2: \(key \leftarrow A[j]\)
3: \(i \leftarrow j - 1\)
4: while \(i > 0\) and \(A[i] > key\) do
5: \(A[i + 1] \leftarrow A[i]\)
6: \(i \leftarrow i - 1\)
7: \(A[i + 1] \leftarrow key\)
Example:

- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

**insertion-sort**($A, n$)

1:  for $j \leftarrow 2$ to $n$ do
2:     key $\leftarrow A[j]$
3:     $i \leftarrow j - 1$
4:     while $i > 0$ and $A[i] > key$ do
5:         $A[i + 1] \leftarrow A[i]$
6:         $i \leftarrow i - 1$
7:     $A[i + 1] \leftarrow key$

- $j = 6$
- $key = 15$

12  21  35  53  53  59

↑  

i
Example:

- **Input:** 53, 12, 35, 21, 59, 15
- **Output:** 12, 15, 21, 35, 53, 59

**insertion-sort**($A, n$)

1: **for** $j \leftarrow 2$ to $n$ **do**
2: \hspace{1em} $key \leftarrow A[j]$
3: \hspace{1em} $i \leftarrow j - 1$
4: \hspace{1em} **while** $i > 0$ and $A[i] > key$ **do**
5: \hspace{2em} $A[i + 1] \leftarrow A[i]$
6: \hspace{2em} $i \leftarrow i - 1$
7: \hspace{1em} $A[i + 1] \leftarrow key$

- $j = 6$
- $key = 15$

12 21 35 53 53 59

↑

$i$
Example:

- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

**insertion-sort**\((A, n)\)

1:  \textbf{for} \(j \leftarrow 2\) \textbf{to} \(n\) \textbf{do}
2:    \(key \leftarrow A[j]\)
3:    \(i \leftarrow j - 1\)
4:  \textbf{while} \(i > 0\) \textbf{and} \(A[i] > key\) \textbf{do}
5:    \(A[i + 1] \leftarrow A[i]\)
6:    \(i \leftarrow i - 1\)
7:  \(A[i + 1] \leftarrow key\)

- \(j = 6\)
- \(key = 15\)

12 21 35 35 53 59

12 21 35 35 53 59

\(i\)
Example:
- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

insertion-sort($A, n$)

1: for $j \leftarrow 2$ to $n$ do
2: \hspace{1em} $key \leftarrow A[j]$
3: \hspace{1em} $i \leftarrow j - 1$
4: \hspace{1em} while $i > 0$ and $A[i] > key$ do
5: \hspace{2em} $A[i + 1] \leftarrow A[i]$
6: \hspace{2em} $i \leftarrow i - 1$
7: \hspace{1em} $A[i + 1] \leftarrow key$

- $j = 6$
- $key = 15$

12 21 35 35 53 59

↑

↓$i$
Example:
- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

insertion-sort(A, n)

1: \textbf{for} \ j \leftarrow 2 \ \textbf{to} \ n \ \textbf{do}
2: \hspace{1em} \textit{key} \leftarrow A[j]
3: \hspace{1em} i \leftarrow j - 1
4: \hspace{1em} \textbf{while} \ i > 0 \ \textbf{and} \ A[i] > \textit{key} \ \textbf{do}
5: \hspace{2em} A[i + 1] \leftarrow A[i]
6: \hspace{1em} i \leftarrow i - 1
7: \hspace{1em} A[i + 1] \leftarrow \textit{key}

- \ j = 6
- \ \textit{key} = 15

12 21 21 35 53 59
^ i
Example:
- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

**insertion-sort(A, n)**

1: for $j \leftarrow 2$ to $n$ do  
2:     $key \leftarrow A[j]$  
3:     $i \leftarrow j - 1$  
4:     while $i > 0$ and $A[i] > key$ do  
5:         $A[i + 1] \leftarrow A[i]$  
6:     $i \leftarrow i - 1$  
7:     $A[i + 1] \leftarrow key$

- $j = 6$
- $key = 15$
Example:

- Input: 53, 12, 35, 21, 59, 15
- Output: 12, 15, 21, 35, 53, 59

insertion-sort($A, n$)

1: for $j \leftarrow 2$ to $n$ do
2: \hspace{1em} key $\leftarrow A[j]$
3: \hspace{1em} $i \leftarrow j - 1$
4: while $i > 0$ and $A[i] > key$ do
5: \hspace{2em} $A[i + 1] \leftarrow A[i]$
6: \hspace{2em} $i \leftarrow i - 1$
7: \hspace{1em} $A[i + 1] \leftarrow key$

- $j = 6$
- $key = 15$

12 15 21 35 53 59

↑

$i$
1 Syllabus

2 Introduction
   - What is an Algorithm?
   - Example: Insertion Sort
   - Analysis of Insertion Sort

3 Asymptotic Notations

4 Common Running times
Analysis of Insertion Sort

- Correctness
- Running time
Correctness of Insertion Sort

Invariant: after iteration $j$ of outer loop, $A[1..j]$ is the sorted array for the original $A[1..j]$.

- after $j = 1$: $53, 12, 35, 21, 59, 15$
- after $j = 2$: $12, 53, 35, 21, 59, 15$
- after $j = 3$: $12, 35, 53, 21, 59, 15$
- after $j = 4$: $12, 21, 35, 53, 59, 15$
- after $j = 5$: $12, 21, 35, 53, 59, 15$
- after $j = 6$: $12, 15, 21, 35, 53, 59$
Analyzing Running Time of Insertion Sort

Q1: what is the size of input?
Q1: what is the size of input?
A1: Running time as the function of size
Q1: what is the size of input?
A1: Running time as the function of size
possible definition of size:
- Sorting problem: \# integers,
- Greatest common divisor: total length of two integers
- Shortest path in a graph: \# edges in graph
Q1: what is the size of input?
A1: Running time as the function of size
possible definition of size:
- Sorting problem: \# integers,
- Greatest common divisor: total length of two integers
- Shortest path in a graph: \# edges in graph

Q2: Which input?
For the insertion sort algorithm: if input array is already sorted in ascending order, then algorithm runs much faster than when it is sorted in descending order.
Analyzing Running Time of Insertion Sort

Q1: what is the size of input?
A1: Running time as the function of size
possible definition of size:
- Sorting problem: \# integers,
- Greatest common divisor: total length of two integers
- Shortest path in a graph: \# edges in graph

Q2: Which input?
- For the insertion sort algorithm: if input array is already sorted in ascending order, then algorithm runs much faster than when it is sorted in descending order.
A2: Worst-case analysis:
- Running time for size $n = \text{worst running time over all possible arrays of length } n$
Q3: How fast is the computer?
Q4: Programming language?
Q3: How fast is the computer?
Q4: Programming language?
A: They do not matter!
Analyzing Running Time of Insertion Sort

- Q3: How fast is the computer?
- Q4: Programming language?
- A: They do not matter!

**Important idea: asymptotic analysis**
- Focus on growth of running-time as a function, not any particular value.
Asymptotic Analysis: $O$-notation

Informal way to define $O$-notation:

- Ignoring lower order terms
- Ignoring leading constant
Asymptotic Analysis: $O$-notation

Informal way to define $O$-notation:

- Ignoring lower order terms
- Ignoring leading constant

$$3n^3 + 2n^2 - 18n + 1028 \Rightarrow 3n^3 \Rightarrow n^3$$
Asymptotic Analysis: $O$-notation

Informal way to define $O$-notation:

- Ignoring lower order terms
- Ignoring leading constant

- $3n^3 + 2n^2 - 18n + 1028 \Rightarrow 3n^3 \Rightarrow n^3$
- $3n^3 + 2n^2 - 18n + 1028 = O(n^3)$
Asymptotic Analysis: $O$-notation

Informal way to define $O$-notation:

- Ignoring lower order terms
- Ignoring leading constant

- $3n^3 + 2n^2 - 18n + 1028 \Rightarrow 3n^3 \Rightarrow n^3$
- $3n^3 + 2n^2 - 18n + 1028 = O(n^3)$
- $n^2/100 - 3n + 10 \Rightarrow n^2/100 \Rightarrow n^2$
Asymptotic Analysis: $O$-notation

Informal way to define $O$-notation:

- Ignoring lower order terms
- Ignoring leading constant

- $3n^3 + 2n^2 - 18n + 1028 \Rightarrow 3n^3 \Rightarrow n^3$
- $3n^3 + 2n^2 - 18n + 1028 = O(n^3)$
- $n^2/100 - 3n + 10 \Rightarrow n^2/100 \Rightarrow n^2$
- $n^2/100 - 3n + 10 = O(n^2)$
Asymptotic Analysis: \( O \)-notation

- \( 3n^3 + 2n^2 - 18n + 1028 = O(n^3) \)
- \( n^2/100 - 3n^2 + 10 = O(n^2) \)
Asymptotic Analysis: $O$-notation

- $3n^3 + 2n^2 - 18n + 1028 = O(n^3)$
- $n^2/100 - 3n^2 + 10 = O(n^2)$

$O$-notation allows us to ignore
- architecture of computer
- programming language
- how we measure the running time: seconds or \# instructions?
Asymptotic Analysis: $O$-notation

- $3n^3 + 2n^2 - 18n + 1028 = O(n^3)$
- $n^2/100 - 3n^2 + 10 = O(n^2)$

$O$-notation allows us to ignore

- architecture of computer
- programming language
- how we measure the running time: seconds or $\#$ instructions?
- to execute $a \leftarrow b + c$:
  - program 1 requires 10 instructions, or $10^{-8}$ seconds
  - program 2 requires 2 instructions, or $10^{-9}$ seconds
Asymptotic Analysis: \( O \)-notation

- \( 3n^3 + 2n^2 - 18n + 1028 = O(n^3) \)
- \( n^2/100 - 3n^2 + 10 = O(n^2) \)

\( O \)-notation allows us to ignore:
- architecture of computer
- programming language
- how we measure the running time: seconds or \# instructions?
- to execute \( a \leftarrow b + c \):
  - program 1 requires 10 instructions, or \( 10^{-8} \) seconds
  - program 2 requires 2 instructions, or \( 10^{-9} \) seconds
  - they only change by a constant in the running time, which will be hidden by the \( O(\cdot) \) notation
Algorithm 1 runs in time $O(n^2)$
Algorithm 2 runs in time $O(n)$
Asymptotic Analysis: $O$-notation

- Algorithm 1 runs in time $O(n^2)$
- Algorithm 2 runs in time $O(n)$
- Does not tell which algorithm is faster for a specific $n$!
Asymptotic Analysis: $O$-notation

- Algorithm 1 runs in time $O(n^2)$
- Algorithm 2 runs in time $O(n)$
- Does not tell which algorithm is faster for a specific $n$!
- Algorithm 2 will eventually beat algorithm 1 as $n$ increases.
Asymptotic Analysis: $O$-notation

- Algorithm 1 runs in time $O(n^2)$
- Algorithm 2 runs in time $O(n)$
- Does not tell which algorithm is faster for a specific $n$!
- Algorithm 2 will eventually beat algorithm 1 as $n$ increases.
- For Algorithm 1: if we increase $n$ by a factor of 2, running time increases by a factor of 4
Asymptotic Analysis: \( O \)-notation

- Algorithm 1 runs in time \( O(n^2) \)
- Algorithm 2 runs in time \( O(n) \)

Does not tell which algorithm is faster for a specific \( n \)!

- Algorithm 2 will eventually beat algorithm 1 as \( n \) increases.

- For Algorithm 1: if we increase \( n \) by a factor of 2, running time increases by a factor of 4
- For Algorithm 2: if we increase \( n \) by a factor of 2, running time increases by a factor of 2
Asymptotic Analysis of Insertion Sort

insertion-sort\((A, n)\)

1: \textbf{for} \(j \leftarrow 2\) to \(n\) \textbf{do}
2: \hspace{1em} \textit{key} \leftarrow A[j]
3: \hspace{1em} \textit{i} \leftarrow j - 1
4: \hspace{1em} \textbf{while} \textit{i} > 0 \text{ and } A[i] > \textit{key} \textbf{do}
5: \hspace{2em} A[i + 1] \leftarrow A[i]
6: \hspace{2em} \textit{i} \leftarrow \textit{i} - 1
7: \hspace{2em} A[i + 1] \leftarrow \textit{key}

Worst-case running time for iteration \(j\) of the outer loop?

Answer: \(O(j)\)

Total running time = \(\sum_{j=2}^{n} O(j) = O(n(n+1)/2 - 1) = O(n^2)\)
Asymptotic Analysis of Insertion Sort

\begin{verbatim}
insertion-sort(A, n)
1: for j ← 2 to n do
2:   key ← A[j]
3:   i ← j - 1
4:   while i > 0 and A[i] > key do
6:     i ← i - 1
7:   A[i + 1] ← key
\end{verbatim}

- Worst-case running time for iteration \( j \) of the outer loop?
Asymptotic Analysis of Insertion Sort

Asymptotic Analysis of Insertion Sort

**insertion-sort**($A$, $n$)

1. **for** $j \leftarrow 2$ **to** $n$ **do**
2.   $key \leftarrow A[j]$
3.   $i \leftarrow j - 1$
4.   **while** $i > 0$ **and** $A[i] > key$ **do**
5.     $A[i + 1] \leftarrow A[i]$
6.   $i \leftarrow i - 1$
7.   $A[i + 1] \leftarrow key$

- Worst-case running time for iteration $j$ of the outer loop?
  
  **Answer:** $O(j)$
Asymptotic Analysis of Insertion Sort

insertion-sort(\(A, n\))

1: \textbf{for } \(j \leftarrow 2\) \textbf{ to } \(n\) \textbf{ do}
2: \hspace{0.5cm} \textit{key} \leftarrow A[j]
3: \hspace{0.5cm} \textit{i} \leftarrow j - 1
4: \hspace{0.5cm} \textbf{while } \textit{i} > 0 \textbf{ and } A[i] > \textit{key} \textbf{ do}
5: \hspace{1.5cm} A[i + 1] \leftarrow A[i]
6: \hspace{1.5cm} \textit{i} \leftarrow \textit{i} - 1
7: \hspace{1.5cm} A[i + 1] \leftarrow \textit{key}

- Worst-case running time for iteration \(j\) of the outer loop?
  Answer: \(O(j)\)

- Total running time \(= \sum_{j=2}^{n} O(j) = O(\sum_{j=2}^{n} j)\)
  \(= O\left(\frac{n(n+1)}{2} - 1\right) = O(n^2)\)
Computation Model

Random-Access Machine (RAM) model

Reading and writing $A[j]$ takes $O(1)$ time.

Basic operations such as addition, subtraction and multiplication take $O(1)$ time.

Each integer (word) has $c \log n$ bits, $c \geq 1$ large enough.

Reason: often we need to read the integer $n$ and handle integers within range $[−n^c, n^c]$, it is convenient to assume this takes $O(1)$ time.

What is the precision of real numbers? Most of the time, we only consider integers.

Can we do better than insertion sort asymptotically? Yes: merge sort, quicksort and heap sort take $O(n \log n)$ time.
Computation Model

- Random-Access Machine (RAM) model
- reading and writing $A[j]$ takes $O(1)$ time

Basic operations such as addition, subtraction and multiplication take $O(1)$ time.

Each integer (word) has $c \log n$ bits, $c \geq 1$ large enough.

Reason: often we need to read the integer $n$ and handle integers within range $\left[-n^c, n^c\right]$, it is convenient to assume this takes $O(1)$ time.

What is the precision of real numbers?

Most of the time, we only consider integers.

Can we do better than insertion sort asymptotically?

Yes: merge sort, quicksort and heap sort take $O(n \log n)$ time.
Computation Model

- Random-Access Machine (RAM) model
  - reading and writing $A[j]$ takes $O(1)$ time
  - Basic operations such as addition, subtraction and multiplication take $O(1)$ time
Computation Model

- Random-Access Machine (RAM) model
  - reading and writing $A[j]$ takes $O(1)$ time
- Basic operations such as addition, subtraction, and multiplication take $O(1)$ time
- Each integer (word) has $c \log n$ bits, $c \geq 1$ large enough
  - Reason: often we need to read the integer $n$ and handle integers within range $[-n^c, n^c]$, it is convenient to assume this takes $O(1)$ time.
Computation Model

- Random-Access Machine (RAM) model
  - reading and writing $A[j]$ takes $O(1)$ time
- Basic operations such as addition, subtraction and multiplication take $O(1)$ time
- Each integer (word) has $c \log n$ bits, $c \geq 1$ large enough
  - Reason: often we need to read the integer $n$ and handle integers within range $[-n^c, n^c]$, it is convenient to assume this takes $O(1)$ time.
- What is the precision of real numbers?
Computation Model

- Random-Access Machine (RAM) model
  - reading and writing $A[j]$ takes $O(1)$ time
- Basic operations such as addition, subtraction and multiplication take $O(1)$ time
- Each integer (word) has $c \log n$ bits, $c \geq 1$ large enough
  - Reason: often we need to read the integer $n$ and handle integers within range $[-n^c, n^c]$, it is convenient to assume this takes $O(1)$ time.
- What is the precision of real numbers?
  Most of the time, we only consider integers.
Computation Model

- Random-Access Machine (RAM) model
  - reading and writing $A[j]$ takes $O(1)$ time
- Basic operations such as addition, subtraction and multiplication take $O(1)$ time
- Each integer (word) has $c \log n$ bits, $c \geq 1$ large enough
  - Reason: often we need to read the integer $n$ and handle integers within range $[-n^c, n^c]$, it is convenient to assume this takes $O(1)$ time.
- What is the precision of real numbers?
  - Most of the time, we only consider integers.
- Can we do better than insertion sort asymptotically?

Yes: merge sort, quicksort and heap sort take $O(n \log n)$ time
Computation Model

- Random-Access Machine (RAM) model
  - reading and writing $A[j]$ takes $O(1)$ time
- Basic operations such as addition, subtraction and multiplication take $O(1)$ time
- Each integer (word) has $c \log n$ bits, $c \geq 1$ large enough
  - Reason: often we need to read the integer $n$ and handle integers within range $[-n^c, n^c]$, it is convenient to assume this takes $O(1)$ time.
- What is the precision of real numbers?
  - Most of the time, we only consider integers.
- Can we do better than insertion sort asymptotically?
  - Yes: merge sort, quicksort and heap sort take $O(n \log n)$ time
Remember to sign up for Piazza.

Questions?
Outline

1. Syllabus

2. Introduction
   - What is an Algorithm?
   - Example: Insertion Sort
   - Analysis of Insertion Sort

3. Asymptotic Notations

4. Common Running times
Asymptotically Positive Functions

**Def.** $f : \mathbb{N} \rightarrow \mathbb{R}$ is an asymptotically positive function if:

- $\exists n_0 > 0$ such that $\forall n > n_0$ we have $f(n) > 0$
Asymptotically Positive Functions

Def. \( f : \mathbb{N} \to \mathbb{R} \) is an asymptotically positive function if:

- \( \exists n_0 > 0 \) such that \( \forall n > n_0 \) we have \( f(n) > 0 \)

- In other words, \( f(n) \) is positive for large enough \( n \).
Def. \( f : \mathbb{N} \rightarrow \mathbb{R} \) is an asymptotically positive function if:

- \( \exists n_0 > 0 \) such that \( \forall n > n_0 \) we have \( f(n) > 0 \)

- In other words, \( f(n) \) is positive for large enough \( n \).
- \( n^2 - n - 30 \)
Asymptotically Positive Functions

**Def.** $f : \mathbb{N} \rightarrow \mathbb{R}$ is an **asymptotically positive function** if:

- $\exists n_0 > 0$ such that $\forall n > n_0$ we have $f(n) > 0$

- In other words, $f(n)$ is positive for large enough $n$.

- $n^2 - n - 30$ \hspace{1cm} Yes
Def. $f : \mathbb{N} \rightarrow \mathbb{R}$ is an asymptotically positive function if:

- $\exists n_0 > 0$ such that $\forall n > n_0$ we have $f(n) > 0$

- In other words, $f(n)$ is positive for large enough $n$.

- $n^2 - n - 30$ Yes

- $2^n - n^{20}$
Asymptotically Positive Functions

**Def.** $f : \mathbb{N} \rightarrow \mathbb{R}$ is an asymptotically positive function if:

- $\exists n_0 > 0$ such that $\forall n > n_0$ we have $f(n) > 0$

- In other words, $f(n)$ is positive for large enough $n$.

- $n^2 - n - 30 \quad \text{Yes}$

- $2^n - n^{20} \quad \text{Yes}$
Asymptotically Positive Functions

Def. $f : \mathbb{N} \to \mathbb{R}$ is an asymptotically positive function if:

- $\exists n_0 > 0$ such that $\forall n > n_0$ we have $f(n) > 0$

- In other words, $f(n)$ is positive for large enough $n$.

- $n^2 - n - 30$ Yes
- $2^n - n^{20}$ Yes
- $100n - n^2/10 + 50$?
Asymptotically Positive Functions

Def. $f : \mathbb{N} \to \mathbb{R}$ is an asymptotically positive function if:

- $\exists n_0 > 0$ such that $\forall n > n_0$ we have $f(n) > 0$

In other words, $f(n)$ is positive for large enough $n$.

- $n^2 - n - 30$ Yes
- $2^n - n^{20}$ Yes
- $100n - n^2 / 10 + 50$? No
Asymptotically Positive Functions

**Def.** $f : \mathbb{N} \rightarrow \mathbb{R}$ is an **asymptotically positive function** if:

- $\exists n_0 > 0$ such that $\forall n > n_0$ we have $f(n) > 0$

In other words, $f(n)$ is positive for large enough $n$.

- $n^2 - n - 30$  Yes
- $2^n - n^{20}$  Yes
- $100n - n^2 / 10 + 50?$  No

We only consider asymptotically positive functions.
O-Notation: Asymptotic Upper Bound

**O-Notation**  For a function \( g(n) \),

\[
O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}.
\]
**O-Notation: Asymptotic Upper Bound**

**O-Notation** For a function $g(n)$,

$$O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}.$$ 

- In other words, $f(n) \in O(g(n))$ if $f(n) \leq cg(n)$ for some $c > 0$ and every large enough $n$. 

$O$-Notation: Asymptotic Upper Bound

$O$-Notation  For a function $g(n)$,

\[
O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}. 
\]

- In other words, $f(n) \in O(g(n))$ if $f(n) \leq cg(n)$ for some $c > 0$ and every large enough $n$. 

![Graph showing $f(n) = O(g(n))$ and $cg(n)$](https://via.placeholder.com/150)
**O-Notation: Asymptotic Upper Bound**

**O-Notation** For a function $g(n)$,

$$O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}.$$ 

- In other words, $f(n) \in O(g(n))$ if $f(n) \leq cg(n)$ for some $c > 0$ and every large enough $n$.
- $3n^2 + 2n \in O(n^2 - 10n)$
**O-Notation: Asymptotic Upper Bound**

**O-Notation** For a function $g(n)$,

$$O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}.$$  

- In other words, $f(n) \in O(g(n))$ if $f(n) \leq cg(n)$ for some $c > 0$ and every large enough $n$.
- $3n^2 + 2n \in O(n^2 - 10n)$

**Proof.**

Let $c = 4$ and $n_0 = 50$, for every $n > n_0 = 50$, we have,

$$3n^2 + 2n - c(n^2 - 10n) = 3n^2 + 2n - 4(n^2 - 10n)$$

$$= -n^2 + 42n \leq 0.$$  

$$3n^2 + 2n \leq c(n^2 - 10n)$$
**O-Notation**  For a function $g(n)$,

$$O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}.$$ 

- In other words, $f(n) \in O(g(n))$ if $f(n) \leq cg(n)$ for some $c$ and large enough $n$.
- $3n^2 + 2n \in O(n^2 - 10n)$
**O-Notation**  For a function \( g(n) \),
\[
O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}.
\]

- In other words, \( f(n) \in O(g(n)) \) if \( f(n) \leq cg(n) \) for some \( c \) and large enough \( n \).
- \( 3n^2 + 2n \in O(n^2 - 10n) \)
- \( 3n^2 + 2n \in O(n^3 - 5n^2) \)
\textbf{O-Notation} For a function \(g(n)\),
\[
O(g(n)) = \left\{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \right\}.
\]

- In other words, \(f(n) \in O(g(n))\) if \(f(n) \leq cg(n)\) for some \(c\) and large enough \(n\).
- \(3n^2 + 2n \in O(n^2 - 10n)\)
- \(3n^2 + 2n \in O(n^3 - 5n^2)\)
- \(n^{100} \in O(2^n)\)
**O-Notation**  For a function \( g(n) \),

\[
O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}. 
\]

- In other words, \( f(n) \in O(g(n)) \) if \( f(n) \leq cg(n) \) for some \( c \) and large enough \( n \).
- \( 3n^2 + 2n \in O(n^2 - 10n) \)
- \( 3n^2 + 2n \in O(n^3 - 5n^2) \)
- \( n^{100} \in O(2^n) \)
- \( n^3 \notin O(10n^2) \)
\textbf{O-Notation}  
For a function \(g(n)\),

\[
O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}.
\]

- In other words, \(f(n) \in O(g(n))\) if \(f(n) \leq cg(n)\) for some \(c\) and large enough \(n\).
- \(3n^2 + 2n \in O(n^2 - 10n)\)
- \(3n^2 + 2n \in O(n^3 - 5n^2)\)
- \(n^{100} \in O(2^n)\)
- \(n^3 \notin O(10n^2)\)

<table>
<thead>
<tr>
<th>Asymptotic Notations</th>
<th>(O)</th>
<th>(\Omega)</th>
<th>(\Theta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Relations</td>
<td>(\leq)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conventions

- We use “\( f(n) = O(g(n)) \)” to denote “\( f(n) \in O(g(n)) \)”
Conventions

- We use \( f(n) = O(g(n)) \) to denote \( f(n) \in O(g(n)) \)
- \( 3n^2 + 2n = O(n^3 - 10n) \)
- \( 3n^2 + 2n = O(n^2 + 5n) \)
- \( 3n^2 + 2n = O(n^2) \)
Conventions

- We use \( f(n) = O(g(n)) \) to denote \( f(n) \in O(g(n)) \)
- \( 3n^2 + 2n = O(n^3 - 10n) \)
- \( 3n^2 + 2n = O(n^2 + 5n) \)
- \( 3n^2 + 2n = O(n^2) \)

“=” is asymmetric! Following equalities are wrong:
- \( O(n^3 - 10n) = 3n^2 + 2n \)
- \( O(n^2 + 5n) = 3n^2 + 2n \)
- \( O(n^2) = 3n^2 + 2n \)

Analogy: Mike is a student.
A student is Mike.
**Conventions**

- We use “\(f(n) = O(g(n))\)” to denote “\(f(n) \in O(g(n))\)”
- \(3n^2 + 2n = O(n^3 - 10n)\)
- \(3n^2 + 2n = O(n^2 + 5n)\)
- \(3n^2 + 2n = O(n^2)\)

“=” is asymmetric! Following equalities are wrong:

- \(O(n^3 - 10n) = 3n^2 + 2n\)
- \(O(n^2 + 5n) = 3n^2 + 2n\)
- \(O(n^2) = 3n^2 + 2n\)

- Analogy: Mike is a student. A student is Mike.
**Ω-Notation: Asymptotic Lower Bound**

**O-Notation** For a function $g(n)$,

$O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}.$

**Ω-Notation** For a function $g(n)$,

$Ω(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \geq cg(n), \forall n \geq n_0 \}.$
**Ω-Notation: Asymptotic Lower Bound**

**O-Notation**  For a function $g(n)$,

$$O(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \leq cg(n), \forall n \geq n_0 \}. $$

**Ω-Notation**  For a function $g(n)$,

$$Ω(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \geq cg(n), \forall n \geq n_0 \}. $$

- In other words, $f(n) \in Ω(g(n))$ if $f(n) \geq cg(n)$ for some $c$ and large enough $n$. 
**Ω-Notation** For a function $g(n)$,

$$\Omega(g(n)) = \{ \text{function } f : \exists c > 0, n_0 > 0 \text{ such that } f(n) \geq cg(n), \forall n \geq n_0 \}.$$
Again, we use “=” instead of ∈.

- $4n^2 = \Omega(n - 10)$
- $3n^2 - n + 10 = \Omega(n^2 - 20)$
Again, we use “=” instead of ∈.

- $4n^2 = \Omega(n - 10)$
- $3n^2 - n + 10 = \Omega(n^2 - 20)$

<table>
<thead>
<tr>
<th>Asymptotic Notations</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Relations</td>
<td>$\leq$</td>
<td>$\geq$</td>
<td></td>
</tr>
</tbody>
</table>
Again, we use “=” instead of \( \in \).

- \( 4n^2 = \Omega(n - 10) \)
- \( 3n^2 - n + 10 = \Omega(n^2 - 20) \)

<table>
<thead>
<tr>
<th>Asymptotic Notations</th>
<th>( O )</th>
<th>( \Omega )</th>
<th>( \Theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Relations</td>
<td>( \leq )</td>
<td>( \geq )</td>
<td></td>
</tr>
</tbody>
</table>

**Theorem** \( f(n) = O(g(n)) \iff g(n) = \Omega(f(n)) \).
\(\Theta\)-Notation: Asymptotic Tight Bound

**\(\Theta\)-Notation** For a function \(g(n)\),

\[
\Theta(g(n)) = \{ \text{function } f : \exists c_2 \geq c_1 > 0, n_0 > 0 \text{ such that } c_1 g(n) \leq f(n) \leq c_2 g(n), \forall n \geq n_0 \}. 
\]
\( \Theta \)-Notation: Asymptotic Tight Bound

\( \Theta \)-Notation  For a function \( g(n) \),

\[ \Theta(g(n)) = \{ \text{function } f : \exists c_2 \geq c_1 > 0, n_0 > 0 \text{ such that} \]
\[ c_1 g(n) \leq f(n) \leq c_2 g(n), \forall n \geq n_0 \} . \]

- \( f(n) = \Theta(g(n)) \), then for large enough \( n \), we have “\( f(n) \approx g(n) \)”.
**Θ-Notation: Asymptotic Tight Bound**

**Θ-Notation**  For a function $g(n)$,

\[ Θ(g(n)) = \{ \text{function } f : \exists c_2 \geq c_1 > 0, n_0 > 0 \text{ such that } c_1 g(n) \leq f(n) \leq c_2 g(n), \forall n \geq n_0 \}. \]

$f(n) = Θ(g(n))$, then for large enough $n$, we have “$f(n) \approx g(n)$”. 

![Graph showing functions $c_1 g(n)$, $f(n)$, and $c_2 g(n)$ with $n_0$ as a vertical dashed line indicating a tight bound.]
\(\Theta\)-Notation: Asymptotic Tight Bound

\(\Theta\)-Notation  For a function \(g(n)\),
\[
\Theta(g(n)) = \{ \text{function } f : \exists c_2 \geq c_1 > 0, n_0 > 0 \text{ such that } \]
\[
c_1 g(n) \leq f(n) \leq c_2 g(n), \forall n \geq n_0 \}.
\]

- \(3n^2 + 2n = \Theta(n^2 - 20n)\)
\(\Theta\)-Notation: Asymptotic Tight Bound

\textbf{\(\Theta\)-Notation}  For a function \(g(n)\),

\[
\Theta(g(n)) = \{ \text{function } f : \exists c_2 \geq c_1 > 0, n_0 > 0 \text{ such that} \]
\[
c_1 g(n) \leq f(n) \leq c_2 g(n), \forall n \geq n_0 \}\.
\]

- \(3n^2 + 2n = \Theta(n^2 - 20n)\)
- \(2^{n/3+100} = \Theta(2^{n/3})\)
**Θ-Notation: Asymptotic Tight Bound**

**Θ-Notation**  For a function $g(n)$,  

$$\Theta(g(n)) = \left\{ \text{function } f : \exists c_2 \geq c_1 > 0, n_0 > 0 \text{ such that } c_1 g(n) \leq f(n) \leq c_2 g(n), \forall n \geq n_0 \right\}.$$  

- $3n^2 + 2n = \Theta(n^2 - 20n)$
- $2^{n/3} + 100 = \Theta(2^{n/3})$

<table>
<thead>
<tr>
<th>Asymptotic Notations</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Relations</td>
<td>$\leq$</td>
<td>$\geq$</td>
<td>$=$</td>
</tr>
</tbody>
</table>
**Θ-Notation: Asymptotic Tight Bound**

**Θ-Notation** For a function $g(n)$,
\[
\Theta(g(n)) = \{ \text{function } f : \exists c_2 \geq c_1 > 0, n_0 > 0 \text{ such that } c_1 g(n) \leq f(n) \leq c_2 g(n), \forall n \geq n_0 \}. 
\]

- $3n^2 + 2n = \Theta(n^2 - 20n)$
- $2^{n/3+100} = \Theta(2^{n/3})$

<table>
<thead>
<tr>
<th>Asymptotic Notations</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Relations</td>
<td>$\leq$</td>
<td>$\geq$</td>
<td>$=$</td>
</tr>
</tbody>
</table>

**Theorem** $f(n) = \Theta(g(n))$ if and only if $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$. 
<table>
<thead>
<tr>
<th>Asymptotic Notations</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Relations</td>
<td>$\leq$</td>
<td>$\geq$</td>
<td>$=$</td>
</tr>
</tbody>
</table>
### Asymptotic Notations

<table>
<thead>
<tr>
<th>Asymptotic Notations</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Relations</td>
<td>$\leq$</td>
<td>$\geq$</td>
<td>$=$</td>
</tr>
</tbody>
</table>

### Trivial Facts on Comparison Relations

- $a \leq b \iff b \geq a$
- $a = b \iff a \leq b$ and $a \geq b$
- $a \leq b$ or $a \geq b$

### Correct Analogies

- $f(n) = O(g(n)) \iff g(n) = \Omega(f(n))$
- $f(n) = \Theta(g(n)) \iff f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$
### Asymptotic Notations

<table>
<thead>
<tr>
<th>Comparison Relations</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\leq$</td>
<td>$\geq$</td>
<td>$=$</td>
</tr>
</tbody>
</table>

### Trivial Facts on Comparison Relations

- $a \leq b \iff b \geq a$
- $a = b \iff a \leq b$ and $a \geq b$
- $a \leq b$ or $a \geq b$

### Correct Analogies

- $f(n) = O(g(n)) \iff g(n) = \Omega(f(n))$
- $f(n) = \Theta(g(n)) \iff f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$
### Asymptotic Notations

<table>
<thead>
<tr>
<th>Comparison Relations</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq$</td>
<td></td>
<td>$\geq$</td>
<td>$=$</td>
</tr>
</tbody>
</table>

### Trivial Facts on Comparison Relations

- $a \leq b \iff b \geq a$
- $a = b \iff a \leq b$ and $a \geq b$
- $a \leq b$ or $a \geq b$

### Correct Analogies

- $f(n) = O(g(n)) \iff g(n) = \Omega(f(n))$
- $f(n) = \Theta(g(n)) \iff f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$

### Incorrect Analogy

- $f(n) = O(g(n))$ or $f(n) = \Omega(g(n))$
Incorrect Analogy

\[ f(n) = O(g(n)) \text{ or } f(n) = \Omega(g(n)) \]
Incorrect Analogy

\[ f(n) = O(g(n)) \text{ or } f(n) = \Omega(g(n)) \]

\[ f(n) = n^2 \]

\[ g(n) = \begin{cases} 
 1 & \text{if } n \text{ is odd} \\
 1 & \text{if } n \text{ is even}
\end{cases} \]
Recall: Informal way to define $O$-notation

- ignoring lower order terms: $3n^2 - 10n - 5 \to 3n^2$
- ignoring leading constant: $3n^2 \to n^2$
Recall: Informal way to define $O$-notation

- ignoring lower order terms: $3n^2 - 10n - 5 \rightarrow 3n^2$
- ignoring leading constant: $3n^2 \rightarrow n^2$
- $3n^2 - 10n - 5 = O(n^2)$
Recall: Informal way to define $O$-notation

- ignoring lower order terms: $3n^2 - 10n - 5 \rightarrow 3n^2$
- ignoring leading constant: $3n^2 \rightarrow n^2$
- $3n^2 - 10n - 5 = O(n^2)$
- Indeed, $3n^2 - 10n - 5 = \Omega(n^2), 3n^2 - 10n - 5 = \Theta(n^2)$
Recall: Informal way to define $O$-notation

- ignoring lower order terms: $3n^2 - 10n - 5 \rightarrow 3n^2$
- ignoring leading constant: $3n^2 \rightarrow n^2$
- $3n^2 - 10n - 5 = O(n^2)$
- Indeed, $3n^2 - 10n - 5 = \Omega(n^2), 3n^2 - 10n - 5 = \Theta(n^2)$
- In the formal definition of $O(\cdot)$, nothing tells us to ignore lower order terms and leading constant.
Recall: Informal way to define $O$-notation

- ignoring lower order terms: $3n^2 - 10n - 5 \rightarrow 3n^2$
- ignoring leading constant: $3n^2 \rightarrow n^2$
- $3n^2 - 10n - 5 = O(n^2)$
- Indeed, $3n^2 - 10n - 5 = \Omega(n^2)$, $3n^2 - 10n - 5 = \Theta(n^2)$
- In the formal definition of $O(\cdot)$, nothing tells us to ignore lower order terms and leading constant.
- $3n^2 - 10n - 5 = O(5n^2 - 6n + 5)$ is correct, though weird
Recall: Informal way to define $O$-notation

- ignoring lower order terms: $3n^2 - 10n - 5 \rightarrow 3n^2$
- ignoring leading constant: $3n^2 \rightarrow n^2$
- $3n^2 - 10n - 5 = O(n^2)$
- Indeed, $3n^2 - 10n - 5 = \Omega(n^2), 3n^2 - 10n - 5 = \Theta(n^2)$
- In the formal definition of $O(\cdot)$, nothing tells us to ignore lower order terms and leading constant.
- $3n^2 - 10n - 5 = O(5n^2 - 6n + 5)$ is correct, though weird
- $3n^2 - 10n - 5 = O(n^2)$ is the most natural since $n^2$ is the simplest term we can have inside $O(\cdot)$. 


Notice that $O$ denotes asymptotic upper bound.

- $n^2 + 2n = O(n^3)$ is correct.
- The following sentence is correct: the running time of the insertion sort algorithm is $O(n^4)$.
- We say: the running time of the insertion sort algorithm is $O(n^2)$ and the bound is tight.
Notice that $O$ denotes asymptotic upper bound

- $n^2 + 2n = O(n^3)$ is correct.
- The following sentence is correct: the running time of the insertion sort algorithm is $O(n^4)$.
- We say: the running time of the insertion sort algorithm is $O(n^2)$ and the bound is tight.
- We do not use $\Omega$ and $\Theta$ very often when we upper bound running times.
Exercise

For each pair of functions \( f, g \) in the following table, indicate whether \( f \) is \( O, \Omega \) or \( \Theta \) of \( g \).

<table>
<thead>
<tr>
<th>( f )</th>
<th>( g )</th>
<th>( O )</th>
<th>( \Omega )</th>
<th>( \Theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n^3 - 100n )</td>
<td>( 5n^2 + 3n )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( 3n - 50 )</td>
<td>( n^2 - 7n )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( n^2 - 100n )</td>
<td>( 5n^2 + 30n )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \log_2 n )</td>
<td>( \log_{10} n )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \log^{10} n )</td>
<td>( n^{0.1} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( 2^n )</td>
<td>( 2^{n/2} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \sqrt{n} )</td>
<td>( n^{\sin n} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We often use \( \log n \) for \( \log_2 n \). But for \( O(\log n) \), the base is not important.
Exercise

For each pair of functions $f, g$ in the following table, indicate whether $f$ is $O$, $\Omega$ or $\Theta$ of $g$.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$g$</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^3 - 100n$</td>
<td>$5n^2 + 3n$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$3n - 50$</td>
<td>$n^2 - 7n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n^2 - 100n$</td>
<td>$5n^2 + 30n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\log_2 n$</td>
<td>$\log_{10} n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\log_{10} n$</td>
<td>$n^{0.1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^n$</td>
<td>$2^{n/2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>$n^{\sin n}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Exercise

For each pair of functions $f, g$ in the following table, indicate whether $f$ is $O, \Omega$ or $\Theta$ of $g$.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$g$</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^3 - 100n$</td>
<td>$5n^2 + 3n$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$3n - 50$</td>
<td>$n^2 - 7n$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$n^2 - 100n$</td>
<td>$5n^2 + 30n$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$\log_2 n$</td>
<td>$\log_{10} n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\log_{10} n$</td>
<td>$n^{0.1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^n$</td>
<td>$2^{n/2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>$n^{{\sin} n}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Exercise

For each pair of functions $f, g$ in the following table, indicate whether $f$ is $O, \Omega$ or $\Theta$ of $g$.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$g$</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^3 - 100n$</td>
<td>$5n^2 + 3n$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$3n - 50$</td>
<td>$n^2 - 7n$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$n^2 - 100n$</td>
<td>$5n^2 + 30n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_2 n$</td>
<td>$\log_{10} n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\log_{10} n$</td>
<td>$n^{0.1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^n$</td>
<td>$2^{n/2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>$n^{\sin n}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Exercise

For each pair of functions $f, g$ in the following table, indicate whether $f$ is $O, \Omega$ or $\Theta$ of $g$.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$g$</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^3 - 100n$</td>
<td>$5n^2 + 3n$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$3n - 50$</td>
<td>$n^2 - 7n$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$n^2 - 100n$</td>
<td>$5n^2 + 30n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_2 n$</td>
<td>$\log_{10} n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_{10} n$</td>
<td>$n^{0.1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^n$</td>
<td>$2^{n/2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>$n^{\sin n}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We often use $\log n$ for $\log_2 n$. But for $O(\log n)$, the base is not important.
Exercise

For each pair of functions $f, g$ in the following table, indicate whether $f$ is $O$, $\Omega$ or $\Theta$ of $g$.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$g$</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^3 - 100n$</td>
<td>$5n^2 + 3n$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$3n - 50$</td>
<td>$n^2 - 7n$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$n^2 - 100n$</td>
<td>$5n^2 + 30n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_2 n$</td>
<td>$\log_{10} n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_{10} n$</td>
<td>$n^{0.1}$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$2^n$</td>
<td>$2^{n/2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>$n^{\sin n}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We often use $\log n$ for $\log_2 n$. But for $O(\log n)$, the base is not important.
Exercise

For each pair of functions $f, g$ in the following table, indicate whether $f$ is $O$, $Ω$ or $Θ$ of $g$.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$g$</th>
<th>$O$</th>
<th>$Ω$</th>
<th>$Θ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^3 - 100n$</td>
<td>$5n^2 + 3n$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$3n - 50$</td>
<td>$n^2 - 7n$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$n^2 - 100n$</td>
<td>$5n^2 + 30n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_2 n$</td>
<td>$\log_{10} n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_{10} n$</td>
<td>$n^{0.1}$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$2^n$</td>
<td>$2^{n/2}$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>$n^{\sin n}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We often use $\log n$ for $\log_2 n$. But for $O(\log n)$, the base is not important.
**Exercise**

For each pair of functions $f, g$ in the following table, indicate whether $f$ is $O$, $Ω$ or $Θ$ of $g$.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$g$</th>
<th>$O$</th>
<th>$Ω$</th>
<th>$Θ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^3 - 100n$</td>
<td>$5n^2 + 3n$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$3n - 50$</td>
<td>$n^2 - 7n$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$n^2 - 100n$</td>
<td>$5n^2 + 30n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_2 n$</td>
<td>$\log_{10} n$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\log_{10} n$</td>
<td>$n^{0.1}$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$2^n$</td>
<td>$2^{n/2}$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>$n^{\sin n}$</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

We often use $\log n$ for $\log_2 n$. But for $O(\log n)$, the base is not important.
<table>
<thead>
<tr>
<th>Asymptotic Notations</th>
<th>$O$</th>
<th>$\Omega$</th>
<th>$\Theta$</th>
<th>$o$</th>
<th>$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Relations</td>
<td>$\leq$</td>
<td>$\geq$</td>
<td>$=$</td>
<td>$&lt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>Asymptotic Notations</td>
<td>$O$</td>
<td>$\Omega$</td>
<td>$\Theta$</td>
<td>$o$</td>
<td>$\omega$</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----</td>
<td>---------</td>
<td>--------</td>
<td>----</td>
<td>-----</td>
</tr>
<tr>
<td>Comparison Relations</td>
<td>$\leq$</td>
<td>$\geq$</td>
<td>$=$</td>
<td>$&lt;$</td>
<td>$&gt;$</td>
</tr>
</tbody>
</table>

Questions?
Outline

1. Syllabus

2. Introduction
   - What is an Algorithm?
   - Example: Insertion Sort
   - Analysis of Insertion Sort

3. Asymptotic Notations

4. Common Running times
Computing the sum of $n$ numbers

\textbf{sum}(A, n)

1: $S \leftarrow 0$
2: for $i \leftarrow 1$ to $n$
3: \hspace{1em} $S \leftarrow S + A[i]$
4: return $S$
Merge two sorted arrays

\[ \begin{array}{cccccc}
3 & 8 & 12 & 20 & 32 & 48 \\
5 & 7 & 9 & 25 & 29 \\
\end{array} \]
$O(n)$ (Linear) Running Time

- Merge two sorted arrays

3 8 12 20 32 48
5 7 9 25 29
$O(n)$ (Linear) Running Time

- Merge two sorted arrays

```
3 8 12 20 32 48
5 7 9 25 29
3
```
Merge two sorted arrays

3 8 12 20 32 48
5 7 9 25 29
3
$O(n)$ (Linear) Running Time

- Merge two sorted arrays

```
3  8  12  20  32  48
5  7  9  25  29
3  5
```
$O(n)$ (Linear) Running Time

- Merge two sorted arrays

```
3 8 12 20 32 48
5 7 9 25 29
3 5
```
Merge two sorted arrays

\[ \begin{array}{cccccc}
3 & 8 & 12 & 20 & 32 & 48 \\
5 & 7 & 9 & 25 & 29 \\
3 & 5 & 7
\end{array} \]
Merge two sorted arrays
Merge two sorted arrays

\[
\begin{array}{cccccc}
3 & 8 & 12 & 20 & 32 & 48 \\
5 & 7 & 9 & 25 & 29 & \\
3 & 5 & 7 & 8 &
\end{array}
\]
$O(n)$ (Linear) Running Time

- Merge two sorted arrays

<table>
<thead>
<tr>
<th>3</th>
<th>8</th>
<th>12</th>
<th>20</th>
<th>32</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>7</td>
<td>9</td>
<td>25</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$O(n)$ (Linear) Running Time

- Merge two sorted arrays

```
3 8 12 20 32 48
5 7 9 25 29
3 5 7 8 9 12 20 25 29
```
Merge two sorted arrays

\[
\begin{array}{ccccccc}
3 & 8 & 12 & 20 & 32 & 48 \\
5 & 7 & 9 & 25 & 29 \\
3 & 5 & 7 & 8 & 9 & 12 & 20 & 25 & 29 & 32 & 48
\end{array}
\]
$O(n)$ (Linear) Running Time

**merge**$(B, C, n_1, n_2)$ \ \ \ \ $\text{\textbackslash\textbackslash} B$ and $C$ are sorted, with length $n_1$ and $n_2$

1. $A \leftarrow \[]$; $i \leftarrow 1$; $j \leftarrow 1$
2. **while** $i \leq n_1$ and $j \leq n_2$ do
3. \ \ \ **if** $B[i] \leq C[j]$ **then**
4. \ \ \ \ \ append $B[i]$ to $A$; $i \leftarrow i + 1$
5. \ \ \ **else**
6. \ \ \ \ \ append $C[j]$ to $A$; $j \leftarrow j + 1$
7. **if** $i \leq n_1$ then append $B[i..n_1]$ to $A$
8. **if** $j \leq n_2$ then append $C[j..n_2]$ to $A$
9. return $A$

Running time = $O(n)$ where $n = n_1 + n_2$. 


merge\((B, C, n_1, n_2)\) \quad \text{B and C are sorted, with length } n_1 \text{ and } n_2

1: A \leftarrow []; i \leftarrow 1; j \leftarrow 1
2: \textbf{while} \ i \leq n_1 \textbf{ and } j \leq n_2 \textbf{ do}
3: \quad \textbf{if} \ B[i] \leq C[j] \textbf{ then}
4: \quad \quad \text{append } B[i] \text{ to } A; \ i \leftarrow i + 1
5: \quad \textbf{else}
6: \quad \quad \text{append } C[j] \text{ to } A; \ j \leftarrow j + 1
7: \quad \textbf{if} \ i \leq n_1 \textbf{ then append } B[i..n_1] \text{ to } A
8: \quad \textbf{if} \ j \leq n_2 \textbf{ then append } C[j..n_2] \text{ to } A
9: \textbf{return} A

Running time = O(n) where n = n_1 + n_2.


\[ O(n \log n) \text{ Running Time} \]

**merge-sort** \((A, n)\)

1. **if** \( n = 1 \) **then**
2. **return** \( A \)
3. \( B \leftarrow \text{merge-sort}\left(A[1..\lfloor n/2 \rfloor], \lfloor n/2 \rfloor\right)\)
4. \( C \leftarrow \text{merge-sort}\left(A[\lfloor n/2 \rfloor + 1..n], n - \lfloor n/2 \rfloor\right)\)
5. **return** \( \text{merge}(B, C, \lfloor n/2 \rfloor, n - \lfloor n/2 \rfloor)\)
$O(n \log n)$ Running Time

- Merge-Sort
$O(n \log n)$ Running Time

- Merge-Sort

Each level takes running time $O(n)$
$O(n \log n)$ Running Time

- **Merge-Sort**

  - Each level takes running time $O(n)$
  - There are $O(\log n)$ levels
**$O(n \log n)$ Running Time**

- Merge-Sort

![Diagram of Merge-Sort](image)

- Each level takes running time $O(n)$
- There are $O(\log n)$ levels
- Running time = $O(n \log n)$
**Closest Pair**

**Input:** $n$ points in plane: $(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$

**Output:** the pair of points that are closest

---

$O(n^2)$ (Quadratic) Running Time
$O(n^2)$ (Quadratic) Running Time

**Closest Pair**

**Input:** $n$ points in plane: $(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$

**Output:** the pair of points that are closest
Closest Pair

**Input:** $n$ points in plane: $(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$

**Output:** the pair of points that are closest

closest-pair($x, y, n$)

1: $bestd \leftarrow \infty$
2: for $i \leftarrow 1$ to $n - 1$ do
3:     for $j \leftarrow i + 1$ to $n$ do
4:         $d \leftarrow \sqrt{(x[i] - x[j])^2 + (y[i] - y[j])^2}$
5:     if $d < bestd$ then
6:         $best_i \leftarrow i, best_j \leftarrow j, bestd \leftarrow d$
7: return $(best_i, best_j)$
Closest Pair

**Input:** $n$ points in plane: $(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)$

**Output:** the pair of points that are closest

close\_pair($x, y, n$)

1. $bestd \leftarrow \infty$
2. for $i \leftarrow 1$ to $n - 1$ do
3. for $j \leftarrow i + 1$ to $n$ do
4. $d \leftarrow \sqrt{(x[i] - x[j])^2 + (y[i] - y[j])^2}$
5. if $d < bestd$ then
6. $besti \leftarrow i, bestj \leftarrow j, bestd \leftarrow d$
7. return $(besti, bestj)$

Closest pair can be solved in $O(n \log n)$ time!
$O(n^3)$ (Cubic) Running Time

Multiply two matrices of size $n \times n$

```ruby
matrix-multiplication(A, B, n)
1: C ← matrix of size $n \times n$, with all entries being 0
2: for $i ← 1$ to $n$ do
3:   for $j ← 1$ to $n$ do
4:     for $k ← 1$ to $n$ do
5:       $C[i, k] ← C[i, k] + A[i, j] \times B[j, k]$
6: return $C$
```
Beyond Polynomial Time: $2^n$

**Def.** An independent set of a graph $G = (V, E)$ is a subset $S \subseteq V$ of vertices such that for every $u, v \in S$, we have $(u, v) \notin E$. 
Def. An independent set of a graph $G = (V, E)$ is a subset $S \subseteq V$ of vertices such that for every $u, v \in S$, we have $(u, v) \notin E$. 
**Def.** An independent set of a graph $G = (V, E)$ is a subset $S \subseteq V$ of vertices such that for every $u, v \in S$, we have $(u, v) \not\in E$. 
Beyond Polynomial Time: \(2^n\)

### Maximum Independent Set Problem

**Input:** graph \(G = (V, E)\)

**Output:** the maximum independent set of \(G\)

### \textproc{max-independent-set}(G = (V, E))

1: \(R \leftarrow \emptyset\)
2: \textbf{for} every set \(S \subseteq V\) \textbf{do}
3: \(b \leftarrow \text{true}\)
4: \textbf{for} every \(u, v \in S\) \textbf{do}
5: \quad \text{if} \ (u, v) \in E \ \text{then} \ b \leftarrow \text{false}
6: \quad \text{if} \ b \ \text{and} \ |S| > |R| \ \text{then} \ R \leftarrow S
7: \text{return} \ R

Running time = \(O(2^n n^2)\).
Beyond Polynomial Time: $n!$

### Hamiltonian Cycle Problem

**Input:** a graph with $n$ vertices

**Output:** a cycle that visits each node exactly once, or say no such cycle exists
Beyond Polynomial Time: \( n! \)

**Hamiltonian Cycle Problem**

**Input:** a graph with \( n \) vertices

**Output:** a cycle that visits each node exactly once, or say no such cycle exists
Beyond Polynomial Time: \( n! \)

Hamiltonian(\( G = (V, E) \))

1. for every permutation \((p_1, p_2, \cdots, p_n)\) of \( V \) do
2. \( b \leftarrow \) true
3. for \( i \leftarrow 1 \) to \( n - 1 \) do
4. \hspace{1em} if \((p_i, p_{i+1}) \notin E\) then \( b \leftarrow \) false
5. \hspace{1em} if \((p_n, p_1) \notin E\) then \( b \leftarrow \) false
6. \hspace{1em} if \( b \) then return \((p_1, p_2, \cdots, p_n)\)
7. return “No Hamiltonian Cycle”

Running time = \( O(n! \times n) \)
$O(\log n)$ (Logarithmic) Running Time

Input: sorted array $A$ of size $n$, an integer $t$;
Output: whether $t$ appears in $A$.

E.g., search 35 in the following array:
\( O(\log n) \) (Logarithmic) Running Time

- Binary search
  - Input: sorted array \( A \) of size \( n \), an integer \( t \);
  - Output: whether \( t \) appears in \( A \).
**$O(\log n)$ (Logarithmic) Running Time**

- Binary search
  - Input: sorted array $A$ of size $n$, an integer $t$;
  - Output: whether $t$ appears in $A$.
- E.g, search 35 in the following array:

<p>| | | | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>8</td>
<td>10</td>
<td>25</td>
<td>29</td>
<td>37</td>
<td>38</td>
<td>42</td>
<td>46</td>
<td>52</td>
<td>59</td>
<td>61</td>
<td>63</td>
<td>75</td>
</tr>
</tbody>
</table>
$O(\log n)$ (Logarithmic) Running Time

- Binary search
  - Input: sorted array $A$ of size $n$, an integer $t$;
  - Output: whether $t$ appears in $A$.
- E.g, search 35 in the following array:

```
3  8  10  25  29  37  38  42  46  52  59  61  63  75  79
```
Binary search

- Input: sorted array $A$ of size $n$, an integer $t$;
- Output: whether $t$ appears in $A$.

E.g., search 35 in the following array:
Binary search
- Input: sorted array $A$ of size $n$, an integer $t$;
- Output: whether $t$ appears in $A$.

E.g, search 35 in the following array:
Binary search

- Input: sorted array $A$ of size $n$, an integer $t$;
- Output: whether $t$ appears in $A$.

E.g, search 35 in the following array:
Binary search
- Input: sorted array $A$ of size $n$, an integer $t$;
- Output: whether $t$ appears in $A$.

E.g, search 35 in the following array:
Binary search

- Input: sorted array $A$ of size $n$, an integer $t$;
- Output: whether $t$ appears in $A$.

E.g., search 35 in the following array:
**$O(\log n)$ (Logarithmic) Running Time**

- Binary search
  - Input: sorted array $A$ of size $n$, an integer $t$;
  - Output: whether $t$ appears in $A$.
- E.g, search 35 in the following array:

```
3 8 10 25 29 37 38 42 46 52 59 61 63 75 79
```
$O(\log n)$ (Logarithmic) Running Time

- Binary search
  - Input: sorted array $A$ of size $n$, an integer $t$;
  - Output: whether $t$ appears in $A$.
- E.g, search 35 in the following array:

```
3  8 10 25 29 37 38 42 46 52 59 61 63 75 79
```
$O(\log n)$ (Logarithmic) Running Time

- Binary search
  - Input: sorted array $A$ of size $n$, an integer $t$;
  - Output: whether $t$ appears in $A$.
- E.g., search 35 in the following array:

```
3  8  10  25  29  37  38  42  46  52  59  61  63  75  79
```

37 > 35
$O(\log n)$ (Logarithmic) Running Time

- Binary search
  - Input: sorted array $A$ of size $n$, an integer $t$;
  - Output: whether $t$ appears in $A$.
- E.g, search 35 in the following array:
Binary search

- Input: sorted array $A$ of size $n$, an integer $t$;
- Output: whether $t$ appears in $A$.

**binary-search($A, n, t$)**

1. $i \leftarrow 1, j \leftarrow n$
2. while $i \leq j$ do
3.   $k \leftarrow \lfloor (i + j)/2 \rfloor$
4.   if $A[k] = t$ return true
5.   if $t < A[k]$ then $j \leftarrow k - 1$ else $i \leftarrow k + 1$
6. return false

$O(\log n)$ (Logarithmic) Running Time
**O(log n) (Logarithmic) Running Time**

Binary search

- Input: sorted array $A$ of size $n$, an integer $t$;
- Output: whether $t$ appears in $A$.

```python
binary-search(A, n, t)
1: $i \leftarrow 1, j \leftarrow n$
2: while $i \leq j$ do
3:     $k \leftarrow \lfloor (i + j)/2 \rfloor$
4:     if $A[k] = t$ return true
5:     if $t < A[k]$ then $j \leftarrow k - 1$ else $i \leftarrow k + 1$
6: return false
```

Running time $= O(\log n)$
Comparing the Orders

- Sort the functions from smallest to largest asymptotically
  $\log n, \ n, \ n^2, \ n \log n, \ n!, \ 2^n, \ e^n, \ n^n$
- $\log n = O(n)$
Comparing the Orders

- Sort the functions from smallest to largest asymptotically: 
  \( \log n, \ n, \ n^2, \ n \log n, \ n!, \ 2^n, \ e^n, \ n^n \)

- \( \log n = O(n) \)

- \( n = O(n^2) \)
Comparing the Orders

- Sort the functions from smallest to largest asymptotically
  \( \log n, \ n, \ n^2, \ n \log n, \ n!, \ 2^n, \ e^n, \ n^n \)
- \( \log n = O(n) \)
- \( n = O(n \log n) \)
- \( n \log n = O(n^2) \)
Comparing the Orders

Sort the functions from smallest to largest asymptotically:

- \( \log n, \ n, \ n^2, \ n \log n, \ n!, \ 2^n, \ e^n, \ n^n \)

- \( \log n = O(n) \)
- \( n = O(n \log n) \)
- \( n \log n = O(n^2) \)
- \( n^2 = O(n!) \)
Comparing the Orders

- Sort the functions from smallest to largest asymptotically
  \[ \log n, \ n, \ n^2, \ n \log n, \ n!, \ 2^n, \ e^n, \ n^n \]
- \( \log n = O(n) \)
- \( n = O(n \log n) \)
- \( n \log n = O(n^2) \)
- \( n^2 = O(2^n) \)
- \( 2^n = O(n!) \)
Comparing the Orders

- Sort the functions from smallest to largest asymptotically
  \( \log n, \ n, \ n^2, \ n \log n, \ n!, \ 2^n, \ e^n, \ n^n \)

- \( \log n = O(n) \)
- \( n = O(n \log n) \)
- \( n \log n = O(n^2) \)
- \( n^2 = O(2^n) \)
- \( 2^n = O(e^n) \)
- \( e^n = O(n!) \)
Comparing the Orders

- Sort the functions from smallest to largest asymptotically:
  \( \log n, \ n, \ n^2, \ n \log n, \ n!, \ 2^n, \ e^n, \ n^n \)

- \( \log n = O(n) \)
- \( n = O(n \log n) \)
- \( n \log n = O(n^2) \)
- \( n^2 = O(2^n) \)
- \( 2^n = O(e^n) \)
- \( e^n = O(n!) \)
- \( n! = O(n^n) \)
Terminologies

When we talk about upper bound on running time:

- Logarithmic time: $O(\log n)$
- Linear time: $O(n)$
- Quadratic time $O(n^2)$
- Cubic time $O(n^3)$
- Polynomial time: $O(n^k)$ for some constant $k$
  - $O(n \log n) \subseteq O(n^{1.1})$. So, an $O(n \log n)$-time algorithm is also a polynomial time algorithm.
- Exponential time: $O(c^n)$ for some $c > 1$
- Sub-linear time: $o(n)$
- Sub-quadratic time: $o(n^2)$
Goal of Algorithm Design

- Design algorithms to minimize the order of the running time.
Goal of Algorithm Design

- Design algorithms to minimize the order of the running time.

- Using asymptotic analysis allows us to ignore the leading constants and lower order terms.
Goal of Algorithm Design

- Design algorithms to minimize the order of the running time.

- Using asymptotic analysis allows us to ignore the leading constants and lower order terms.

- Makes our life much easier! (E.g., the leading constant depends on the implementation, compiler and computer architecture of computer.)
Q: Does ignoring the leading constant cause any issues?

- e.g., how can we compare an algorithm with running time $0.1n^2$ with an algorithm with running time $1000n$?
Q: Does ignoring the leading constant cause any issues?

- e.g., how can we compare an algorithm with running time $0.1n^2$ with an algorithm with running time $1000n$?

A:
Q: Does ignoring the leading constant cause any issues?

- e.g., how can we compare an algorithm with running time $0.1n^2$ with an algorithm with running time $1000n$?

A:

- Sometimes yes
Q: Does ignoring the leading constant cause any issues?

- e.g, how can we compare an algorithm with running time $0.1n^2$ with an algorithm with running time $1000n$?

A:

- Sometimes yes
- However, when $n$ is big enough, $1000n < 0.1n^2$
Q: Does ignoring the leading constant cause any issues?

- e.g, how can we compare an algorithm with running time $0.1n^2$ with an algorithm with running time $1000n$?

A:

- Sometimes yes
- However, when $n$ is big enough, $1000n < 0.1n^2$
- For “natural” algorithms, constants are not so big!
Q: Does ignoring the leading constant cause any issues?

- e.g., how can we compare an algorithm with running time $0.1n^2$ with an algorithm with running time $1000n$?

A:

- Sometimes yes
- However, when $n$ is big enough, $1000n < 0.1n^2$
- For “natural” algorithms, constants are not so big!
- So, for reasonably large $n$, algorithm with lower order running time beats algorithm with higher order running time.