CSE 431/531: Algorithm Analysis and Design (Spring 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: 9:00am-9:50am, NSC 201
- Instructor:
  - Shi Li, shil@buffalo.edu
- TAs and Graders:
  - Sean Sanders, Xiaoyu Zhang,
  - Graders: TBD
You should already have/know:
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- **Mathematical Background**
- basic reasoning skills, inductive proofs
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- **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
  - · · ·

NP-completeness
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

<table>
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<tr>
<th>Topic</th>
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<tr>
<td>Introduction</td>
<td>4 lectures</td>
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<td>Graph Basics</td>
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<td>Greedy Algorithms</td>
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<td>Divide and Conquer</td>
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<td>Dynamic Programming</td>
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<td>NP-Completenessness</td>
<td>5 lectures</td>
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<td>2 lectures</td>
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- **50 Minutes/Lecture × 42 Lectures**
Textbook

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

- 40% for theory homeworks
  - 8 points \times 5 theory homeworks
- 20% for programming problems
  - 10 points \times 2 programming assignments
- 40% 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 for three days
- 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
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Questions?
Outline

1. Syllabus

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

3. Asymptotic Notations

4. Common Running times
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2. Introduction
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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.
Examples

Greatest Common Divisor

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

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

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- 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

$$\text{gcd}(270, 210) = \text{gcd}(210, 270 \mod 210) = \text{gcd}(210, 60)$$
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
  - \( \text{gcd}(270, 210) = \text{gcd}(210, 270 \mod 210) = \text{gcd}(210, 60) \)
  - \((270, 210) \rightarrow (210, 60) \rightarrow (60, 30) \rightarrow (30, 0)\)
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 $a'_1 \leq a'_2 \leq \cdots \leq a'_n$
Examples

Sorting

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

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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, ...
### 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 labeled edges and nodes]
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 $G$

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

C++ program:

```cpp
int Euclidean(int a, int b) {
    int c;
    while (b > 0) {
        c = b;
        b = a % b;
        a = c;
    }
    return a;
}
```
Main focus: correctness, running time (efficiency)
Theoretical Analysis of Algorithms

- Main focus: correctness, running time (efficiency)
- Sometimes: memory usage
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- Not covered in the course: engineering side
  - extensibility
  - modularity
  - object-oriented model
  - user-friendliness (e.g., GUI)
  - ...
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Why is it important to study the running time (efficiency) of an algorithm?
Main focus: correctness, running time (efficiency)

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

1. feasible vs. infeasible
Main focus: correctness, running time (efficiency)
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Why is it important to study the running time (efficiency) of an algorithm?
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2. efficient algorithms: less engineering tricks needed, can use languages aiming for easy programming (e.g, python)
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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
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  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!
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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 ← 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
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 59 15

$\uparrow$

$i$
Example:

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

insertion-sort$(A, n)$

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Example:
- **Input:** 53, 12, 35, 21, 59, 15
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**insertion-sort**(A, n)

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

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- $key = 15$

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↑

↑ $i$
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. \(A[i + 1] \leftarrow key\)

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

```
12  21  35  35  53  59
```

\[ \uparrow \]

\[ i \]
Example:
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**insertion-sort**$(A, n)$

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Analysis of Insertion Sort

- Correctness
- Running time
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
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.
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 $n = \text{worst running time over all possible arrays of length } n$
Analyzing Running Time of Insertion Sort

- 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

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- Ignoring lower order terms
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\[
3n^3 + 2n^2 - 18n + 1028 \Rightarrow 3n^3 \Rightarrow n^3
\]
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:
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\[
3n^3 + 2n^2 - 18n + 1028 \Rightarrow 3n^3 \Rightarrow n^3 \\
3n^3 + 2n^2 - 18n + 1028 = O(n^3) \\
n^2/100 - 3n + 10 \Rightarrow n^2/100 \Rightarrow n^2
\]
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

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

- $3n^3 + 2n^2 - 18n + 1028 = O(n^3)$
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$O$-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 $a ← b + c$:
- 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 $O(n)$
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 $O(n^2)$
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- Does not tell which algorithm is faster for a specific $n$!
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- For Algorithm 1: if we increase $n$ by a factor of 2, running time increases by a factor of 4
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: 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

Worst-case running time for iteration $j$ of the outer loop?

Answer: $O(j)$

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

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Computation Model

Random-Access Machine (RAM) model

Reading and writing a[i] 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

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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:

\[ \exists n_0 > 0 \text{ such that } \forall n > n_0 \text{ we have } f(n) > 0 \]
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We only consider asymptotically positive functions.
Def. $f : \mathbb{N} \rightarrow \mathbb{R}$ is an \textbf{asymptotically positive function} if:

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- $n^2 - n - 30$
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We only consider asymptotically positive functions.
**O-Notation: Asymptotic Upper Bound**

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

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

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

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

$$= -n^2 + 40n \leq 0.$$

$$3n^2 + 2n \leq c(n^2 - 10n)$$
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Conventions

- We use “$f(n) = O(g(n))$” to denote “$f(n) \in O(g(n))$”
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Analogy: Mike is a student. A student is Mike.
\(\Omega\)-Notation: Asymptotic Lower Bound

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

**\(\Omega\)-Notation**  For a function \(g(n)\),
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\]
**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: Asymptotic Lower Bound**

**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 $\in$.

- $4n^2 = \Omega(n - 10)$
- $3n^2 - n + 10 = \Omega(n^2 - 20)$
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\[ \Omega - \text{Notation: Asymptotic Lower Bound} \]

- Again, we use “\(=\)” instead of \(\in\).
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**Theorem**  
\[ f(n) = O(g(n)) \iff g(n) = \Omega(f(n)). \]
\( \Theta \)-\textbf{Notation: Asymptotic Tight Bound}

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

**Θ-Notation** For a function $g(n)$,

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

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

**Θ-Notation**  For a function $g(n)$,
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\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 \}.
\]

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

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

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

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

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

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

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\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\}.
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- \(3n^2 + 2n = \Theta(n^2 - 20n)\)
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**Theorem** \(f(n) = \Theta(g(n))\) if and only if \(f(n) = O(g(n))\) and \(f(n) = \Omega(g(n))\).
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**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 $a \geq b$
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**Trivial Facts on Comparison Relations**
- $a \leq b \iff b \geq a$
- $a = b \iff a \leq b \text{ and } a \geq b$
- $a \leq b \text{ or } a \geq b$

**Correct Analogies**
- $f(n) = O(g(n)) \iff g(n) = \Omega(f(n))$
- $f(n) = \Theta(g(n)) \iff f(n) = O(g(n)) \text{ and } f(n) = \Omega(g(n))$
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**Trivial Facts on Comparison Relations**

- $a \leq b \iff b \geq a$
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**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

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

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

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

\[ g(n) = \begin{cases} 
1 & \text{if } n \text{ is odd} \\
n^3 & \text{if } n \text{ is even}
\end{cases} \]
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: $3n^2 - 10n - 5 \to 3n^2$
- ignoring leading constant: $3n^2 \to n^2$
- $3n^2 - 10n - 5 = O(n^2)$
- Indeed, $3n^2 - 10n - 5 = \Omega(n^2)$, $3n^2 - 10n - 5 = \Theta(n^2)$
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In the formal definition of $O(\cdot)$, nothing tells us to ignore lower order terms and leading constant.
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- ignoring lower order terms: $3n^2 - 10n - 5 \rightarrow 3n^2$
- ignoring leading constant: $3n^2 \rightarrow n^2$
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- 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 $g$.

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<thead>
<tr>
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<td></td>
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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: $S \leftarrow S + A[i]$
4: return $S$
O(n) (Linear) Running Time

- Merge two sorted arrays

<p>| | | | | | |</p>
<table>
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<tbody>
<tr>
<td>3</td>
<td>8</td>
<td>12</td>
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<td>32</td>
<td>48</td>
</tr>
<tr>
<td>---</td>
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$O(n)$ (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
Merge two sorted arrays
Merge two sorted arrays

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

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

- Merge two sorted arrays

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$O(n)$ (Linear) Running Time

- Merge two sorted arrays

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

- Merge two sorted arrays

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

- Merge two sorted arrays

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

3 8 12 20 32 48
5 7 9 25 29
3 5 7 8 9 12 20 25 29 32 48
merge($B, C, n_1, n_2$) \ \ \ \ \ \ \ \ $B$ 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: \hspace{1em} if $B[i] \leq C[j]$ then
4: \hspace{2em} append $B[i]$ to $A$; $i \leftarrow i + 1$
5: \hspace{1em} else
6: \hspace{2em} 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 $A$

$O(n)$ (Linear) Running Time

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

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

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

Running time = $O(n)$ where $n = n_1 + n_2$. 
**$O(n \log n)$ Running Time**

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

1: \textbf{if} $n = 1$ \textbf{then} \\
2: \hspace{1em} \textbf{return} $A$ \\
3: \textbf{else} \\
4: \hspace{1em} $B \leftarrow \text{merge-sort}\left(A[1..\lfloor n/2 \rfloor], \lfloor n/2 \rfloor\right)$ \\
5: \hspace{1em} $C \leftarrow \text{merge-sort}\left(A[\lceil n/2 \rceil + 1..n], n - \lfloor n/2 \rfloor\right)$ \\
6: \hspace{1em} \textbf{return} \text{merge($B, C, \lfloor n/2 \rfloor, n - \lfloor n/2 \rfloor$)}
Running Time

- **Merge-Sort**

Each level takes running time $O(n)$. There are $O(\log n)$ levels. Therefore, the running time is $O(n \log n)$. 

![Diagram of Merge-Sort tree](image-url)
$O(n \log n)$ 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**

  ![Merge-Sort Diagram]

  
  - Each level takes running time $O(n)$
  - There are $O(\log n)$ levels
  - Running time = $O(n \log n)$
\(O(n^2)\) (Quadratic) Running Time

**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
Closest Pair

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**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.         $besti \leftarrow i, bestj \leftarrow j, bestd \leftarrow d$
7. **return** $(besti, bestj)$

$O(n^2)$ (Quardatic) Running Time
Closest Pair

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

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```plaintext
closest-pair(x, y, n)

1: bestd ← ∞
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5:             if $d < bestd$ then
6:                 besti ← $i$, bestj ← $j$, bestd ← $d$
7:         return (besti, bestj)
```

Closest pair can be solved in $O(n \log n)$ time!
Multiply two matrices of size $n \times n$

**matrix-multiplication**(A, B, n)

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

**Maximum Independent Set Problem**

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

**Output:** the maximum independent set of $G$

**Algorithm:**

1. $R \leftarrow \emptyset$
2. for every set $S \subseteq V$ do
3.   $b \leftarrow \text{true}$
4.   for every $u, v \in S$ do
5.     if $(u, v) \in E$ then $b \leftarrow \text{false}$
6.   if $b$ and $|S| > |R|$ then $R \leftarrow S$
7. 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 ($p_1, p_2, \ldots, p_n$) of $V$ **do**
2. \hspace{1em} $b \leftarrow$ true
3. \hspace{1em} **for** $i \leftarrow 1$ to $n - 1$ **do**
4. \hspace{2em} \hspace{1em} **if** ($p_i, p_{i+1}$) $\notin E$ \hspace{1em} **then** $b \leftarrow$ false
5. \hspace{2em} \hspace{1em} **if** ($p_n, p_1$) $\notin E$ \hspace{1em} **then** $b \leftarrow$ false
6. \hspace{2em} \hspace{1em} **if** $b$ \hspace{1em} **then** return ($p_1, p_2, \ldots, p_n$)
7. **return** “No Hamiltonian Cycle”

Running time = $O(n! \times n)$
$O\left(\log n\right)$ (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 $A$. 

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

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  - Output: whether $t$ appears in $A$.

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

<table>
<thead>
<tr>
<th>3</th>
<th>8</th>
<th>10</th>
<th>25</th>
<th>29</th>
<th>37</th>
<th>38</th>
<th>42</th>
<th>46</th>
<th>52</th>
<th>59</th>
<th>61</th>
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- E.g, search 35 in the following array:

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

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25 < 35
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37 > 35
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$O(\log n)$ (Logarithmic) Running Time

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. \[ \text{if } A[k] = t \text{ return } \text{true} \]
5. \[ \text{if } t < A[k] \text{ then } j \leftarrow k - 1 \text{ else } i \leftarrow k + 1 \]
6. **return** false
**O(log n) (Logarithmic) Running Time**

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: \hspace{1em} $k \leftarrow \lfloor (i + j)/2 \rfloor$
4: \hspace{1em} **if** $A[k] = t$ **return** $true$
5: \hspace{1em} **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
  \( \log n, \ n, \ n^2, \ n \log n, \ n!, \ 2^n, \ e^n, \ n^n \)
- \( \log n = O(n) \)
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- \( e^n = O(n!) \)
- \( n! = O(n^n) \)
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.
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- Using asymptotic analysis allows us to ignore the leading constants and lower order terms.
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- 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 $1000n$?

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.
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A:
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