

# Introduction to Number Theory and Algorithms

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## Prerequisites

### Theorem 0.1: Common Derivatives

Power Rule: For  $n \neq 0$

$$\frac{d}{dx}(x^n) = n \cdot x^{n-1} . \text{ E.g., } \frac{d}{dx}(x^2) = 2x$$

Derivative of a Constant:

$$\frac{d}{dx}(c) = 0 . \text{ E.g., } \frac{d}{dx}(5) = 0$$

Derivative of  $\ln x$ :

$$\frac{d}{dx}(\ln x) = \frac{1}{x}$$

Derivative of  $\log_a x$ :

$$\frac{d}{dx}(\log_a x) = \frac{1}{x \ln a}$$

Derivative of  $\sqrt{x}$ :

$$\frac{d}{dx}(\sqrt{x}) = \frac{1}{2\sqrt{x}}$$

Derivative of function  $f(x)$ :

$$\frac{d}{dx}(x) = 1 . \text{ E.g., } \frac{d}{dx}(5x) = 5$$

Derivative of the Exponential Function:

$$\frac{d}{dx}(e^x) = e^x$$

### Theorem 0.2: L'Hopital's Rule

Let  $f(x)$  and  $g(x)$  be two functions. If  $\lim_{x \rightarrow a} f(x) = 0$  and  $\lim_{x \rightarrow a} g(x) = 0$ , or  $\lim_{x \rightarrow a} f(x) = \pm\infty$  and  $\lim_{x \rightarrow a} g(x) = \pm\infty$ , then:

$$\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(x)}{g'(x)}$$

Where  $f'(x)$  and  $g'(x)$  are the derivatives of  $f(x)$  and  $g(x)$  respectively.

**Theorem 0.3: Exponents Rules**

For  $a, b, x \in \mathbb{R}$ , we have:

$$x^a \cdot x^b = x^{a+b} \text{ and } (x^a)^b = x^{ab}$$

$$x^a \cdot y^a = (xy)^a \text{ and } \frac{x^a}{y^a} = \left(\frac{x}{y}\right)^a$$

**Note:** The  $:=$  symbol is short for “is defined as.” For example,  $x := y$  means  $x$  is defined as  $y$ .

**Definition 0.1: Logarithm**

Let  $a, x \in \mathbb{R}$ ,  $a > 0$ ,  $a \neq 1$ . Logarithm  $x$  base  $a$  is denoted as  $\log_a(x)$ , and is defined as:

$$\log_a(x) = y \iff a^y = x$$

Meaning  $\log$  is inverse of the exponential function, i.e.,  $\log_a(x) := (a^y)^{-1}$ .

**Tip:** To remember the order  $\log_a(x) = a^y$ , think, “base  $a$ ,” as  $a$  is the base of our  $\log$  and  $y$ .

**Theorem 0.4: Logarithm Rules**

For  $a, b, x \in \mathbb{R}$ , we have:

$$\log_a(x) + \log_a(y) = \log_a(xy) \text{ and } \log_a(x) - \log_a(y) = \log_a\left(\frac{x}{y}\right)$$

$$\log_a(x^b) = b \log_a(x) \text{ and } \log_a(x) = \frac{\log_b(x)}{\log_b(a)}$$

**Definition 0.2: Permutations**

Let  $n$  be a positive integer. Then the number of distinct ways to arrange  $n$  objects in order is it's *permutation*. Denoted:

$$n! := n \cdot (n - 1) \cdot (n - 2) \cdot \dots \cdot 2 \cdot 1$$

**Definition 0.3: Combinations**

Let  $n$  and  $k$  be positive integers. Where order doesn't matter, the number of distinct ways to choose  $k$  objects from  $n$  objects is it's *combination*. Denoted:

$$\binom{n}{k} := \frac{n!}{k!(n-k)!}$$

Where  $\binom{n}{k}$  is read as “ $n$  choose  $k$ ”, and  $(\cdot)$ , the *binomial coefficient*.

**Theorem 0.5: Binomial Theorem**

Let  $a$  and  $b$  be real numbers, and  $n$  a non-negative integer. The binomial expansion of  $(a+b)^n$  is given by:

$$(a+b)^n = \sum_{k=0}^n \binom{n}{k} a^{n-k} b^k$$

which expands explicitly as:

$$(a+b)^n = \binom{n}{0} a^n + \binom{n}{1} a^{n-1} b + \binom{n}{2} a^{n-2} b^2 + \dots + \binom{n}{n-1} a b^{n-1} + \binom{n}{n} b^n$$

where  $\binom{n}{k}$  represents the binomial coefficient, defined as:

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$

for  $0 \leq k \leq n$ .

**Theorem 0.6: Binomial Expansion of  $2^n$** 

For any non-negative integer  $n$ , the following identity holds:

$$2^n = \sum_{i=0}^n \binom{n}{i} = (1+1)^n.$$

**Definition 0.4: Well-Ordering Principle**

Every non-empty set of positive integers has a least element.

**Definition 0.5: “Without Loss of Generality”**

A phrase that indicates that the proceeding logic also applies to the other cases. i.e., For a proposition not to lose the assumption that it works other ways as well.

**Theorem 0.7: Pigeon Hole Principle**

Let  $n, m \in \mathbb{Z}^+$  with  $n < m$ . Then if we distribute  $m$  pigeons into  $n$  pigeonholes, there must be at least one pigeonhole with more than one pigeon.

**Theorem 0.8: Growth Rate Comparisons**

Let  $n$  be a positive integer. The following inequalities show the growth rate of some common functions in increasing order:

$$1 < \log n < n < n \log n < n^2 < n^3 < 2^n < n!$$

These inequalities indicate that as  $n$  grows larger, each function on the right-hand side grows faster than the ones to its left.

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## Introduction to Runtime Complexity

### 1.1 Asymptotic Notation

Asymptotic analysis is a method for describing the limiting behavior of functions as inputs grow infinitely.

#### Definition 1.1: Asymptotic

Let  $f(n)$  and  $g(n)$  be two functions. As  $n$  grows, if  $f(n)$  grows closer to  $g(n)$  never reaching, we say that " $f(n)$  is asymptotic to  $g(n)$ ."

We call the point where  $f(n)$  starts behaving similarly to  $g(n)$  the threshold  $n_0$ . After this point  $n_0$ ,  $f(n)$  follows the same general path as  $g(n)$ .

#### Definition 1.2: Big-O: (Upper Bound)

Let  $f$  and  $g$  be functions.  $f(n)$  our function of interest, and  $g(n)$  our function of comparison.

Then we say  $f(n) = O(g(n))$ , " $f(n)$  is big-O of  $g(n)$ ," if  $f(n)$  grows no faster than  $g(n)$ , up to a constant factor. Let  $n_0$  be our asymptotic threshold. Then, for all  $n \geq n_0$ ,

$$0 \leq f(n) \leq c \cdot g(n)$$

Represented as the ratio  $\frac{f(n)}{g(n)} \leq c$  for all  $n \geq n_0$ . Analytically we write,

$$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} < \infty$$

Meaning, as we chase infinity, our numerator grows slower than the denominator, bounded, never reaching infinity.

**Examples:**

(i.)  $3n^2 + 2n + 1 = O(n^2)$

(ii.)  $n^{100} = O(2^n)$

(iii.)  $\log n = O(\sqrt{n})$

**Proof 1.1:**  $\log n = O(\sqrt{n})$

We setup our ratio:

$$\lim_{n \rightarrow \infty} \frac{\log n}{\sqrt{n}}$$

Since  $\log n$  and  $\sqrt{n}$  grow infinitely without bound, they are of indeterminate form  $\frac{\infty}{\infty}$ . We apply L'Hopital's Rule, which states that taking derivatives of the numerator and denominator will yield an evaluateable limit:

$$\lim_{n \rightarrow \infty} \frac{\log n}{\sqrt{n}} = \lim_{n \rightarrow \infty} \frac{\frac{d}{dn} \log n}{\frac{d}{dn} \sqrt{n}}$$

Yielding derivatives,  $\log n = \frac{1}{n}$  and  $\sqrt{n} = \frac{1}{2\sqrt{n}}$ . We substitute these back into our limit:

$$\lim_{n \rightarrow \infty} \frac{\frac{1}{n}}{\frac{1}{2\sqrt{n}}} = \lim_{n \rightarrow \infty} \frac{2\sqrt{n}}{n} = \lim_{n \rightarrow \infty} \frac{2}{\sqrt{n}} = 0$$

Our limit approaches 0, as we have a constant factor in the numerator, and a growing denominator. Thus,  $\log n = O(\sqrt{n})$ , as  $0 < \infty$ . ■

**Definition 1.3: Big- $\Omega$ : (Lower Bound)**

The symbol  $\Omega$  reads “Omega.” Let  $f$  and  $g$  be functions. Then  $f(n) = \Omega(g(n))$  if  $f(n)$  grows no slower than  $g(n)$ , up to a constant factor. I.e., lower bounded by  $g(n)$ . Let  $n_0$  be our asymptotic threshold. Then, for all  $n \geq n_0$ ,

$$0 \leq c \cdot g(n) \leq f(n)$$

$$0 < \lim_{n \rightarrow \infty} \frac{f(n)}{g(n)}$$

Meaning, as we chase infinity, our numerator grows faster than the denominator, approaching 0 asymptotically.

**Examples:**  $n! = \Omega(2^n)$ ;  $\frac{n}{100} = \Omega(n)$ ;  $n^{3/2} = \Omega(\sqrt{n})$ ;  $\sqrt{n} = \Omega(\log n)$

**Definition 1.4: Big  $\Theta$ : (Tight Bound)**

The symbol  $\Theta$  reads “Theta.” Let  $f$  and  $g$  be functions. Then  $f(n) = \Theta(g(n))$  if  $f(n)$  grows at the same rate as  $g(n)$ , up to a constant factor. I.e.,  $f(n)$  is both upper and lower bounded by  $g(n)$ . Let  $n_0$  be our asymptotic threshold, and  $c_1 > 0, c_2 > 0$  be some constants. Then, for all  $n \geq n_0$ ,

$$0 \leq c_1 \cdot g(n) \leq f(n) \leq c_2 \cdot g(n)$$

$$0 < \lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} < \infty$$

Meaning, as we chase infinity, our numerator grows at the same rate as the denominator.

**Examples:**  $n^2 = \Theta(n^2)$ ;  $2n^3 + 2n = \Theta(n^3)$ ;  $\log n + \sqrt{n} = \Theta(\sqrt{n})$ .

**Tip:** To review:

- **Big-O:**  $f(n) < g(n)$  (Upper Bound);  $f(n)$  grows no faster than  $g(n)$ .
- **Big- $\Omega$ :**  $f(n) > g(n)$  (Lower Bound);  $f(n)$  grows no slower than  $g(n)$ .
- **Big- $\Theta$ :**  $f(n) = g(n)$  (Tight Bound);  $f(n)$  grows at the same rate as  $g(n)$ .

**Theorem 1.1: Types of Asymptotic Behavior**

The following are common relationships between different types of functions and their asymptotic growth rates:

- **Polynomials.** Let  $f(n) = a_0 + a_1n + \dots + a_dn^d$  with  $a_d > 0$ . Then,  $f(n)$  is  $\Theta(n^d)$ . E.e.,  $3n^2 + 2n + 1$  is  $\Theta(n^2)$ .
- **Logarithms.**  $\Theta(\log_a n)$  is  $\Theta(\log_b n)$  for any constants  $a, b > 0$ . That is, logarithmic functions in different bases have the same growth rate. E.g.,  $\log_2 n$  is  $\Theta(\log_3 n)$ .
- **Logarithms and Polynomials.** For every  $d > 0$ ,  $\log n$  is  $O(n^d)$ . This indicates that logarithms grow slower than any polynomial. E.g.,  $\log n$  is  $O(n^2)$ .
- **Exponentials and Polynomials.** For every  $r > 1$  and every  $d > 0$ ,  $n^d$  is  $O(r^n)$ . This means that exponentials grow faster than any polynomial. E.e.,  $n^2$  is  $O(2^n)$ .

## 1.2 Evaluating Algorithms

When analyzing algorithms, we are interested in two primary factors: time and space complexity.

### Definition 2.1: Time Complexity

The **time complexity** of an algorithm is the amount of time it takes to run as a function of the input size. We use asymptotic notation to describe the time complexity of an algorithm.

### Definition 2.2: Space Complexity

The **space complexity** of an algorithm is the amount of memory it uses to store inputs and subsequent variables during the algorithm's execution. We use asymptotic notation to describe the space complexity of an algorithm.

Below is an example of a function and its time and space complexity analysis.

### Function 2.1: Arithmetic Series - $\text{Fun1}(A)$

Computes a result based on a length- $n$  array of integers:

**Input:** A length- $n$  array of integers.

**Output:** An integer  $p$  computed from the array elements.

```

1 Function  $\text{Fun1}(A)$ :
2    $p \leftarrow 0$ ;
3   for  $i \leftarrow 1$  to  $n - 1$  do
4     for  $j \leftarrow i + 1$  to  $n$  do
5        $p \leftarrow p + A[i] \cdot A[j]$ ;
6     end
7   end
8 return  $p$ 
```

**Time Complexity:** For  $f(n) := \text{Fun1}(A)$ ,  $f(n) = \frac{n^2}{2} = O(n^2)$ . This is because the function has a nested loop structure, where the inner for-loop runs  $n - i$  times, and the outer for-loop runs  $n - 1$  times. Thus, the total number of iterations is  $\sum_{i=1}^{n-1} n - i = \frac{n^2}{2}$ .

**Space Complexity:** We yield  $O(n)$  for storing an array of length  $n$ . The variable  $p$  is  $O(1)$  (constant), as it is a single integer. Hence,  $f(n) = n + 1 = O(n)$ .

**Additional Example:** Let  $f(n, m) = n^2m + m^3 + nm^3$ . Then,  $f(n, m) = O(n^2m + m^3)$ . This is because both  $n$  and  $m$  must be accounted for. Our largest  $n$  term is  $n^2m$ , and our largest  $m$  term is  $m^3$  both dominate the expression. Thus,  $f(n, m) = O(n^2m + m^3)$ .

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## Proving Algorithms

### 2.1 Stable Matchings

In proving the correctness of algorithms we introduce the stable matching problem. A combinatorial optimization problem that seeks to find the best possible matching between two sets of elements. When we say “best possible matching,” we mean that the matching is stable, and that there is no other matching that is better.

#### Definition 1.1: Stable Matching

A matching is **stable** if there is no pair of elements that prefer each other over their current match.

#### Definition 1.2: Unstable Matching

A matching is **unstable** if there is a pair of elements that prefer each other over their current match.

I.e., in verifying a stable matching, if any one pair of elements switch partners, the matching is unstable. If no pairs swap, the matching is stable.

#### Scenario: Lunch Time

Imagine it's lunch time at elementary school, and a group of kids  $E = \{\text{Ena, Eda}\}$  swap lunches with  $A = \{\text{Ava, Adi}\}$ . They each have a list of preferences from favorite to least favorite. We visualize the following preferences:

E's Preference List		A's Preference List	
	1st	2nd	
Ena	Ava	Adi	Ava
Eda	Ava	Adi	Ena

Observe the following matchings:

- (1.) Pairs, Ena-Ava, Eda-Adi swapped lunches.

E's Preference List		A's Preference List	
	1st	2nd	
Ena	Ava	Adi	Ava
Eda	Ava	Adi	Adi

E's Preference List		A's Preference List	
	1st	2nd	
Ava	Ena	Eda	Ena
Adi	Eda	Ena	Eda

This matching is **stable**. Ena and Ava prefer each other's lunches. Eda will ask Ava to trade, and Ava will refuse because she prefers Ena's lunch. Adi does the same with Ena, but they also refuse.

**Tip:** If it's hard to keep track who is who, here's a possible order to read in: Ena got Ava, and Ena is their 1st choice. Eda got Adi, and Eda is their 2nd choice.

Changing the preference tables,

- (2.) Pairs, Ena-Adi, Eda-Ava swapped lunches.

E's Preference List		A's Preference List	
	1st	2nd	
Ena	Ava	Adi	Ava
Eda	Adi	Ava	Adi

E's Preference List		A's Preference List	
	1st	2nd	
Ava	Ena	Eda	Ena
Adi	Eda	Ena	Eda

This matching is **unstable**. Ena and Ava would rather eat each other's lunches.

**Definition 1.3: Unique Stable Matching**

A matching is **uniquely stable** if between two sets of elements, there is only one possible stable matching.

**Example:** If everyone uniquely prefers each other, there is only one stable matching.

(3.) Pairs, Ena-Ava, Eda-Adi swapped lunches.

E's Preference List			A's Preference List		
	1st	2nd		1st	2nd
Ena	Ava	Adi	Ava	Ena	Eda
Eda	Adi	Ava	Adi	Eda	Ena

This matching is a **unique stable matching**. If rather Ena-Adi and Eda-Ava (2nd-choice parings), then both pairs would end up swapping to their 1st-choice. **Notably:** for table sizes of  $n \times n$ , then  $0 < n \leq 2$  forces a unique stable matching.

## 2.2 Gale-Shapley Algorithm

We will now introduce the Gale-Shapley algorithm, for which we will prove its correctness, time complexity, and space complexity.

### Theorem 2.1: Gale-Shapley Algorithm

The **Gale-Shapley algorithm** is a method for finding a stable matching between two sets of elements. It is also known as the **Deferred Acceptance Algorithm**.

**Algorithm:** Given sets  $E = e_1, \dots, e_n$  and  $A = a_1, \dots, a_n$ . Then find a stable matching:

- (i.) Each  $e_i \in E$  proposes to their most preferred  $a_j$ .
- (ii.) For each  $a_j \in A$ :
  - (a.) If  $a_j$  is free, they accept the proposal.
  - (b.) If  $a_j$  is already matched,  $a_j$  either accepts or rejects. If  $a_j$  accepts, the previous match is broken.

Each  $e_i$  continues to propose to their next most preferred  $a_j$  until all  $e_i$  are matched.

### Claims:

1. At least one stable matching is guaranteed.
2. Unless the table is unique, the proposing will always get their best choice unless it conflicts with another proposer.

First we will prove the correctness, then implement the algorithm and analyze its time and space complexity.

**Proof 2.1: Gale-Shapley Algorithm Correctness**

**Claim 1:** Suppose, for sake of contradiction, that some  $a_j \in A$  is not matched upon termination of the algorithm. Then some  $e_i \in E$  is also not matched assuming  $|E| = |A|$ . Then  $e_i$  must have not proposed to  $a_j$ , contradicting that  $e_i$  proposed to all elements of  $A$ . Thus, the program only terminates when all  $e_i$  are matched.

**Claim 2:** Suppose  $E$  proposes to  $A$  with unique first choices. Then all  $a_i \in A$  must accept their first proposal. Now suppose  $e_i, e_j \in E$  have a conflicting choice  $a_i$ . Then  $a_i$  gets their preference only in that case. ■

**Function 2.1: Gale-Shapley Algorithm - GS( $E, A$ )**

Finds a stable matching between two sets of elements:

**Input:** Two sets,  $E$  and  $A$ , of equal size.

**Output:** A stable matching between  $E$  and  $A$ .

```

1 Function GS( $E, A$ ):
2    $M \leftarrow \emptyset;$ 
3   while there is some unmatched element in  $E$  do
4      $e \leftarrow$  next unmatched element in  $E$ ;
5      $a \leftarrow$  next available preferred choice of  $e$ ;
6     if  $a$  is not yet matched then
7       match  $e$  and  $a$ ;
8       add the pair  $(e, a)$  to  $M$ ;
9     end
10    else
11      if  $a$  prefers  $e$  over their current match then
12        match  $e$  and  $a$ , replacing the current match;
13        update  $M$  accordingly;
14      end
15    end
16  end
17  return  $M$ ;
18 return Matching  $M$ 

```

**Time Complexity:**  $O(n^2)$  time, where  $n$  is the number of elements in  $E$  and  $A$ . Worst-case, each element in  $E$  proposes to each element in  $A$ , i.e.,  $n \cdot n$  combinations to check.

**Space Complexity:**  $O(n^2)$  space, where we store  $|E| \cdot |A| = n \cdot n$  pairs.

### 3.1 Paths and Connectivity

Graphs are similar to train networks or airline routes. They connect one location to another.

#### Definition 1.1: Graph

A **graph** is a collection of points, called **vertices** or **nodes**, connected by lines, called **edges**. Similarly to how a polygon has vertices connected by edges.

#### Definition 1.2: Undirected Graph

An **undirected graph** is a graph where the edges have no particular direction going both ways between nodes. A **degree** of a node is the number of edges connected to it.

**Example:** Figure (3.1) shows an undirected graph:

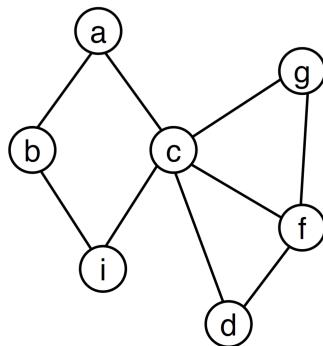


Figure 3.1: An undirected graph with 7 vertices and 9 edges.

Node *a* has a degree of 3, and node *c* has a degree of 4.

**Definition 1.3: Directed Graph**

A **directed graph** is where the edges have a specific direction from one node to another.

- The **indegree** of a node is the number of edges that point to it.
- The **outdegree** of a node is the number of edges that point from it.

**Example:** Figure (3.2) shows a directed graph:

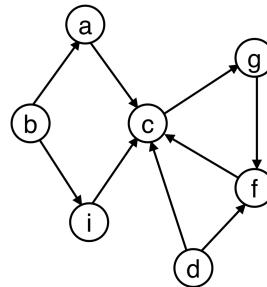


Figure 3.2: A directed graph with 7 vertices and 9 edges.

Node *b* has an outdegree of 2 and an indegree of 0. *c* has an indegree of 4 and an outdegree of 0.

**Definition 1.4: Weighted Graph**

A **weighted graph** is a graph where each edge has a numerical value assigned to it.

**Example:** Figure (3.3) shows a weighted graph:

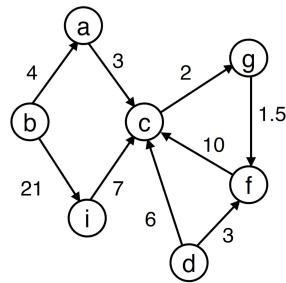


Figure 3.3: A weighted graph with 7 vertices and 9 edges.

**Definition 1.5: Path**

A **path** is a sequence of edges that connect a sequence of vertices. A path is **simple** if all nodes are distinct.

**Example:** In Figure (3.4), a simple path  $h \leftrightarrow b \leftrightarrow i \leftrightarrow c \leftrightarrow d$  is shown:

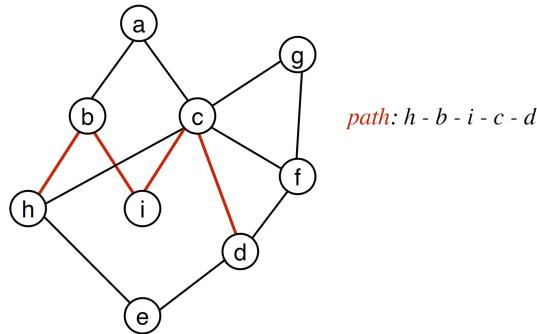


Figure 3.4: A graph with a simple path from  $h$  to  $d$ .

**Definition 1.6: Connectivity**

A graph is **connected** if there is a path between every pair of vertices.

A graph is **disconnected** if there are two vertices with no path between them.

Connected graphs of  $n$  nodes have at least  $n - 1$  edges.

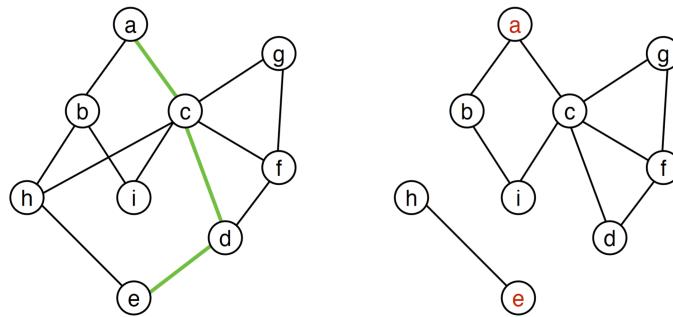


Figure 3.5: A connected graph  $a \leftrightarrow c \leftrightarrow d \leftrightarrow e$  and disconnected graph.

### Definition 1.7: Adjacency Matrix

An **adjacency matrix** is an  $n \times n$  matrix where such that  $A[i][j] = 1$  if there is an edge between nodes  $i$  and  $j$ .

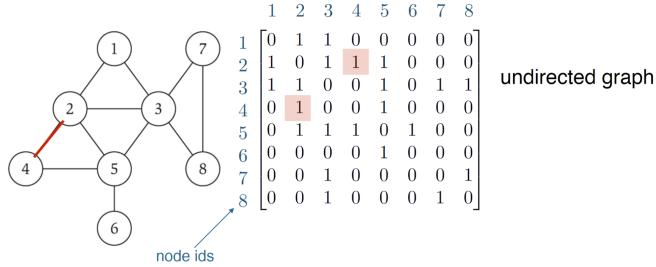


Figure 3.6: An adjacency matrix where the path  $4 \leftrightarrow 2$  is highlighted ( $A[2][4]$  or  $A[4][2]$ )

### Theorem 1.1: Properties of Adjacency Matrix

The following properties hold for adjacency matrices:

- An undirected graph is symmetric about the diagonal.
- A directed graph is not symmetric about.
- A weighted graph has the weight of the edge instead of binary.

**Space Complexity:**  $\Theta(n^2)$ ; **Time Complexities:**

**Check edges  $A[i][j]$ :**  $\Theta(1)$ ; **List neighbors  $A[i]$ :**  $\Theta(n)$ ; **List all edges:**  $\Theta(n^2)$ .

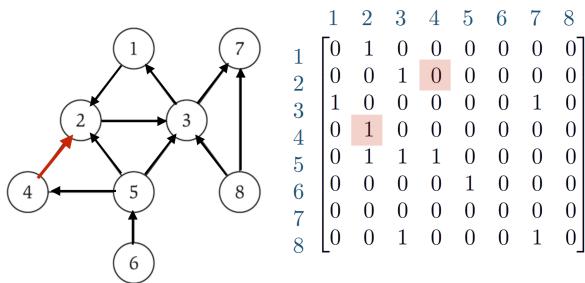


Figure 3.7: An adjacency matrix for a directed graph with path  $4 \leftrightarrow 2$  highlighted ( $A[2][4]$  and  $A[4][2]$ ).

**Definition 1.8: Adjacency List**

An **adjacency list** is a list of keys where each key has a list of neighbors.

Often taking form as a dictionary or hash-table:

**Space Complexity:**  $\Theta(n + m)$  for  $n$  nodes and  $m$  total edges; **Time Complexities:**

**Check key:**  $\Theta(1)$ ; **List neighbors:**  $\Theta(|\text{outdegrees}| \text{ of key})$ ; **List all edges:**  $\Theta(n + m)$ ;  
**Insert edge:**  $\Theta(1)$ .

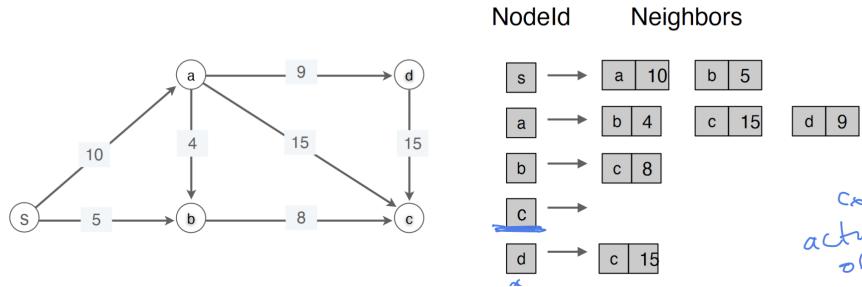


Figure 3.8: An adjacency list of a directed graph,  $c$  highlighted with no outdegrees.

## 3.2 Breath-First and Depth-First Search

Two general methods for traversing a graph are, **breadth-first search** and **depth-first search**.

**Definition 2.1: Cycle**

A **cycle** is a path that starts and ends at the same node.

**Example:** In the above Figure (3.7),  $1 \rightarrow 2 \rightarrow 3 \rightarrow 1$  form a cycle.

**Definition 2.2: Tree**

A **tree** is a connected graph with no cycles. A **leaf-nodes** is the outer-most nodes of a tree.  
A **branch** is a path from the root to a leaf.

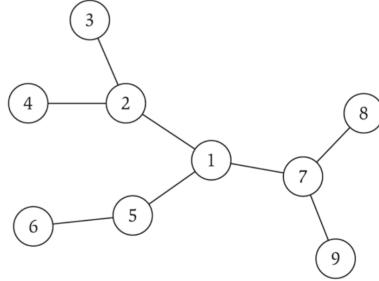
**Theorem 2.1: Tree Identity**

Let  $G$  be an undirected graph of  $n$  nodes. Then any two statements imply the third:

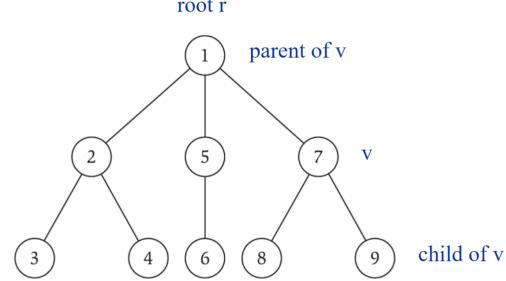
- (i.)  $G$  is connected.
- (ii.)  $G$  has  $n - 1$  edges.
- (iii.)  $G$  has no cycles.

**Definition 2.3: Rooted Trees**

Let  $T$  be a tree with a designated root node  $r$ . Then each degree is considered an outdegree, called a **child**, and its indegree its **parent**.



a tree



the same tree, rooted at 1

Figure 3.9: A rooted tree with root 1 and children  $\{2, 5, 7\}$ **Definition 2.4: Levels and Heights**

The **level** of a node is the number of edges from the root. The **height** of a tree is the maximum level of any node.

**Example:** In Figure (3.9)'s rooted tree , node 5 has a level of 1, and the height of the tree is 2.

**Definition 2.5: Breadth-First Search (BFS)**

In a **breadth-first search**, we start at a node's children first before moving onto their children's children in level order.

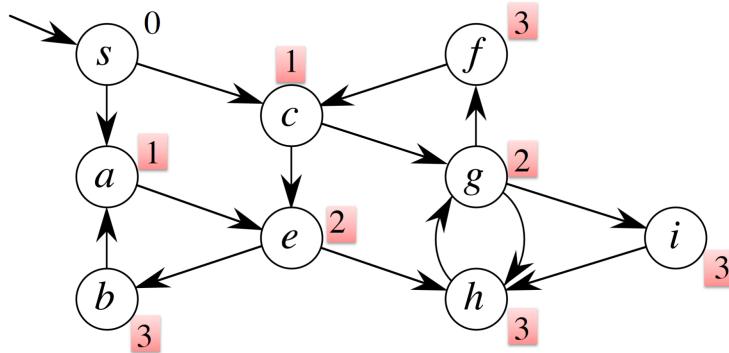


Figure 3.10: A BFS tree traversal preformed on a graph with each level enumerated

**Theorem 2.2: Properties of BFS**

BFS run on any graph  $T$  produces a tree  $T'$  with the following properties:

- (i.)  $T'$  is a tree.
- (ii.)  $T'$  is a rooted tree with the starting node as the root.
- (iii.) The height of  $T'$  is the shortest path from the root to any node.
- (iv.) Any sub-paths of  $T'$  are also shortest paths.

**Proof 2.1: Proof of BFS**

(i.) and (ii.) follow from the definition of a tree. (iii.) and (iv.) follow that since a tree contains a direct path to any given node in our parent child relationship, that path must be the shortest.  $\blacksquare$

**Tip:** In a family tree, there is only one path from each ancestor to each descendant.

We create a BFS algorithm from what we know, though not the best implementation:

**Function 2.1: BFS Algorithm -  $\text{BFS}(s)$**

Breadth-First Search starting from node  $s$ .

**Input:** Graph  $G = (V, E)$  and starting node  $s$ .

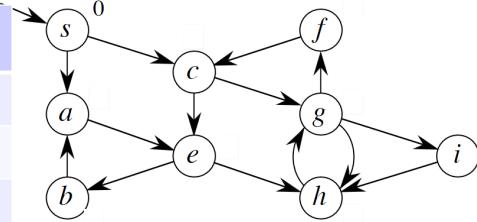
**Output:** Levels of each vertex from  $s$ .

```

1 Function  $\text{BFS}(s)$ :
2   for each  $v \in V$  do
3     | Level[ $v$ ]  $\leftarrow \infty$ ;
4   end
5   Level[ $s$ ]  $\leftarrow 0$ ;
6   Add  $s$  to  $Q$ ;
7   while  $Q$  not empty do
8     |  $u \leftarrow Q.\text{Dequeue}()$ ;
9     | for each  $v \in G[u]$  do
10    |   | if Level[ $v$ ]  $= \infty$  then
11    |   |   | Add edge  $(u, v)$  to tree  $T$  (parent[ $v$ ]  $= u$ );
12    |   |   | Add  $v$  to  $Q$ ;
13    |   |   | Level[ $v$ ]  $\leftarrow$  Level[ $u$ ] + 1;
14    |   end
15   end
16 end

```

$u$	Queue contents before exploring $u$	... after exploring $u$
$s$	(empty)	$[a, c]$
$a$	$[c]$	$[c, e]$
$c$	$[e]$	$[e, g]$
$e$	$[g]$	$[g, b, h]$
$g$	$[b, h]$	$[b, h, f, i]$
$b$	$[h, f, i]$	$[h, f, i]$
$h$	$[f, i]$	$[f, i]$
$f$	$[i]$	$[i]$
$i$	(empty)	(empty)



**Loop invariant:** If the first node in the queue has level  $i$ , then the queue consists of nodes of level  $i$  possibly followed by nodes of level  $i + 1$ .

**Consequence:** Nodes are explored in increasing order of level.

Figure 3.11: A table showing the queue at each level of iteration

We analyze the time and space complexity in the below Figure (3.12):

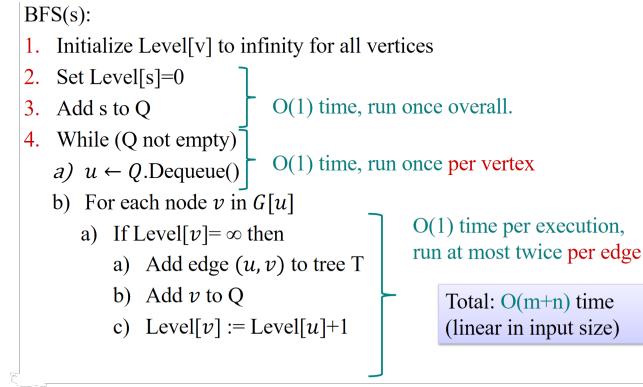


Figure 3.12: An analysis showing  $O(m + n)$  for both time and space complexity

### Proof 2.2: Claim 1 for BFS

Let  $s$  be the root of the BFS tree, then: **Proof:** Induction on the distance from  $s$  to  $u$ .

**Base case** ( $u = s$ ): The code sets  $\text{Level}[s] = 0$ , and there is no path to find since the path has length 0.

**Induction hypothesis:** For every node  $u$  at distance  $\leq i$ , Claim 1 holds.

**Induction step:**

- Let  $v$  be a node at distance exactly  $i + 1$  from  $s$ . Let  $u$  be its parent in the BFS tree.
- The code sets  $\text{Level}[v] = \text{Level}[u] + 1$ .
- Let  $x$  be the last node before  $v$  on a shortest path from  $s$  to  $v$ . Since  $v$  is at distance  $i + 1$ , then  $x$  must be at distance  $i$ , and so  $\text{Level}[x] = i$  (by induction hypothesis).
- If  $u = x$ , we are done!
- If  $u \neq x$ , then it must be that  $u$  was explored before  $x$ , since otherwise  $x$  would be the parent of  $u$ .
- Since we explore nodes in order of level,  $\text{Level}[u] \leq \text{Level}[x] = i$ .
- If  $\text{Level}[u] = i$ , then we are done.
- If  $\text{Level}[u] < i$ , then the path  $s \sim u \rightarrow v$  has length at most  $i$ , which contradicts the assumption that the distance of  $v$  is  $i + 1$ .

We conclude that  $\text{Level}[u] = i$ ,  $\text{Level}[v] = i + 1$ , and the path in the BFS tree that goes from  $s$  to  $u$  to  $v$  has length  $i + 1$ . QED. ■

**Definition 2.6: Types of Edges**

In graphs we have three types of edges:

1. **Tree-edges:** An Edge present in a BFS tree.
2. **Forward-edges:** Edges from an ancestor to a descendant.
3. **Back-edges:** Edges from a descendant to an ancestor.
4. **Cross-edges:** Edges between which connect nodes that have no ancestor-descendant relationship.

**Example:** In Figure (3.10),  $\{(s, c), (a, c), \dots\}$  are forward and tree edges,  $\{(g, h)\}$  are cross edges.

The following arises from the above definitions:

**Theorem 2.3: BFS does not Contain Back-edges**

In a BFS tree, there are no back-edges, as they would create a cycle.

**Note:** In Figure (3.10),  $b \rightarrow a$  is not a tree-edge,  $a$  is on level 1 and  $b$  on level 3. If this connection were to occur, it would create a cycle, breaking our tree.

**Definition 2.7: Depth-First Search (DFS)**

In a **depth-first search**, we recursively explore each an entire branch before moving onto the next.

**Function 2.2: DFS Algorithm -  $\text{DFS}(G)$** 

Depth-First Search on graph  $G$  (recursive).

**Input:** Graph  $G = (V, E)$ .

**Output:** Discovery and finishing times for each vertex.

```

1 Function  $\text{DFS}(G)$ :
2   for each  $u \in G$  do
3     |  $u.\text{state} \leftarrow \text{unvisited}$ ;
4   end
5   time  $\leftarrow 0$ ;
6   for each  $u \in G$  do
7     | if  $u.\text{state} == \text{unvisited}$  then
8       | |  $\text{DFS-Visit}(u)$ ;
9     | end
10   end

11 Function  $\text{DFS-Visit}(u)$ :
12   time  $\leftarrow$  time + 1;
13    $u.d \leftarrow$  time ;
14   // record discovery time;
15    $u.\text{state} \leftarrow \text{discovered}$ ;
16   for each  $v \in G[u]$  do
17     | if  $v.\text{state} == \text{unvisited}$  then
18       | |  $\text{DFS-Visit}(v)$ ;
19     | end
20   end
21    $u.\text{state} \leftarrow \text{finished}$ ;
22   time  $\leftarrow$  time + 1;
23    $u.f \leftarrow$  time;
24   // record finishing time;
```

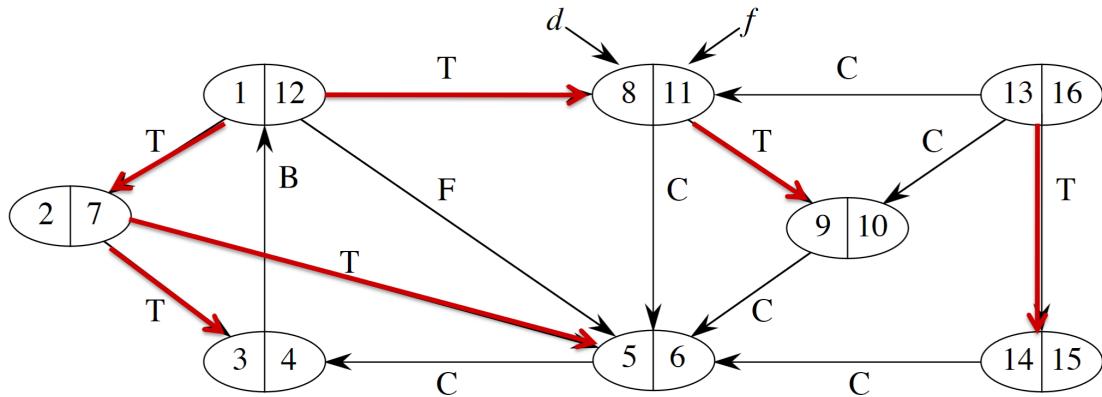
**Time and Space Complexity:**  $O(n + m)$  where  $n$  is the number of vertices and  $m$  the number of edges.

**Proof 2.3: DFS Correctness**

**Case 1:** When  $s$  is discovered, there is a path of unvisited vertices from  $s$  to  $y$ . We use induction on the length  $L$  of the unvisited path from  $x$  to  $y$ .

- **Base case:** There is an edge  $(x, y)$ , and  $y$  is unvisited.
- **Induction hypothesis:** Assume that the claim is true for all nodes reachable via  $k$  unvisited nodes.
- **Induction step:**
  - Consider  $u$  reachable via  $k + 1$  unvisited nodes.
  - Let  $z$  be the last node on the path before  $y$ , and  $z$  is discovered from  $x$  (by I.H.).
  - The edge  $(z, y)$  will be explored from  $x$ , ensuring that  $y$  is eventually visited.

Thus,  $\text{DFS-Visit}(x)$  explores all nodes reachable from  $x$  through a path of unvisited nodes, as required.  $\blacksquare$



- $T$  = tree edge (drawn in red)
- $F$  = forward edge (to a *descendant* in DFS forest)
- $B$  = back edge (to an *ancestor* in DFS forest)
- $C$  = cross edge (goes to a vertex that is neither ancestor nor descendant)

Figure 3.13: A graph showing our  $d$  discovered and  $f$  finished times, denoted in pairs  $(f, d)$ .

**Theorem 2.4: DFS and Cycles**

Let DFS run on graph  $G$ , then:

$$(G \text{ has a cycle}) \iff (\text{DFS run reveals back edges})$$

**Proof 2.4: Proof of Cycles and Back Edges**

**Proving** ( $G$  has a cycle)  $\iff$  (DFS run reveals back edges): Every back edge creates a cycle.

**Proving** ( $G$  has a cycle)  $\implies$  (DFS run reveals back edges) Suppose  $G$  has a cycle:

- Let  $u_1$  be the first discovered vertex in the cycle, and let  $u_k$  be its predecessor in the cycle.
- $u_k$  will be discovered while exploring  $u_1$ .
- The edge  $(u_k, u_1)$  will be a back edge.

■

### 3.3 Directed-Acyclic Graphs & Topological Ordering

Graphs may represent a variety of relationships, such as dependencies between tasks or the flow of information.

**Definition 3.1: Directed-Acyclic Graph (DAG)**

**directed-acyclic graph** is a directed graph with no cycles.

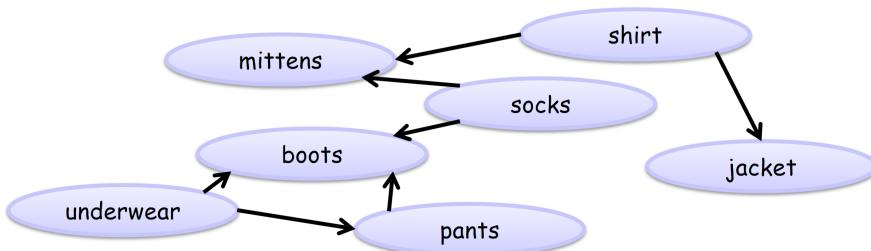


Figure 3.14: A DAG depicted by getting dressed for winter.

For each node to be processed its **dependencies** or parents must be processed first.

**Definition 3.2: Topological Ordering**

Given a graph, a **topological ordering** is a linear ordering of nodes such that for every edge  $(u, v)$ ,  $u$  comes before  $v$ .

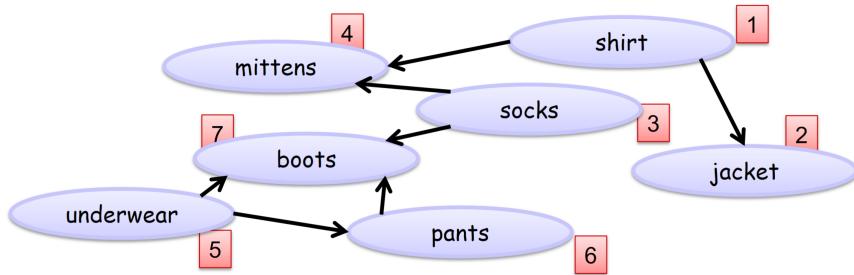


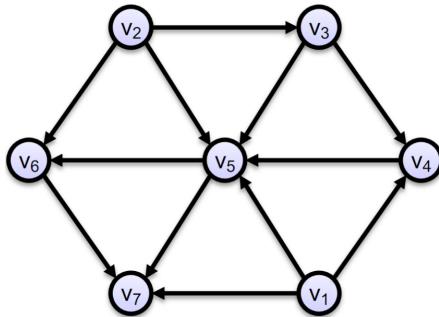
Figure 3.15: A topological ordering of the DAG in Figure (3.14) enumerated in red.

Another possible ordering of  $[1, 2, 3, 4, 5, 6, 7]$  is  $[5, 6, 1, 2, 3, 4, 7]$ , as  $5 \rightarrow 6$  is independent.

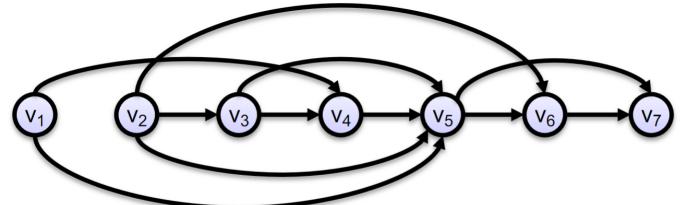
**Theorem 3.1: Topological Sort**

iven a DAG, a topological ordering can be found.

$$(v_i, v_j) \in E \Rightarrow i < j$$



a DAG



a topological ordering

Figure 3.16: A topological sorting of a DAG  $E$  and  $v$  nodes

**Proof 3.1: Topological Sort via DFS**

**Lemma:** In a directed graph  $G$ , if (note necessarily acyclic):

- $(u, v)$  is an edge, and
- $v$  is not reachable from  $u$ ,

Then in every run of DFS,  $u.f > v.f$ .

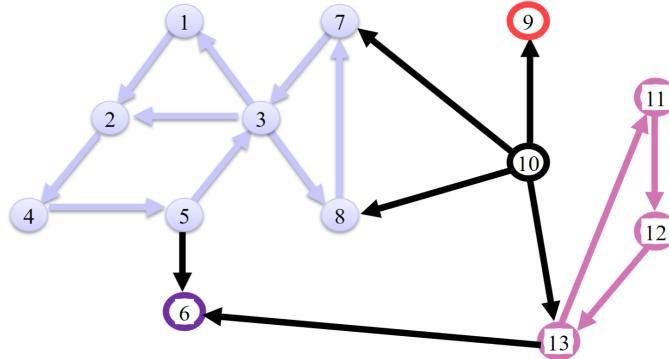
**Proof:**

- If  $v$  is started before  $u$ , then the  $\text{DFS-Visit}(v)$  will terminate without reaching  $u$  (because there is no path to  $u$ ).
- If  $u$  is started before  $v$ , then the edge  $(u, v)$  will be explored before  $u$  is finished.

Therefore, in all cases,  $u.f > v.f$ . ■

**Definition 3.3: Strongly Connected Components**

A **strongly connected component** is a subgraph where every node is reachable from every other node. Then we say  $u \rightsquigarrow v$  and  $v \rightsquigarrow u$  are **mutually reachable**.



- **Observation.** Two SCCs are either disjoint or equal.
- If we contract the SC components in one node we get an *acyclic* graph.

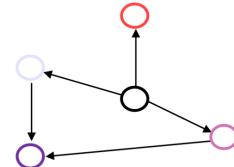


Figure 3.17: A graph with 5 strongly connected components.

#### 4.1 Interval Scheduling

Scheduling problems arise in many areas, such as scheduling classes, tasks, or jobs. Interval scheduling is a type of scheduling problem where we want to maximize the number of tasks we can complete.

##### Definition 1.1: Schedule

A **schedule** is a set of tasks which we call **jobs**. Each job has a start time  $s_i$  and an end time  $f_i$ . Two jobs are **compatible** if they do not overlap.

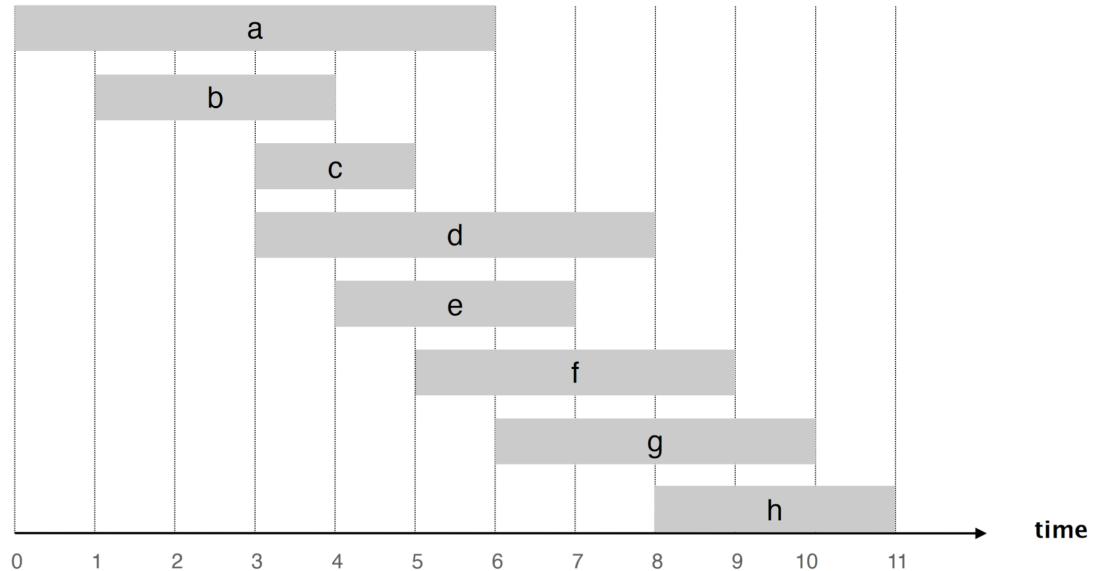


Figure 4.1: Given jobs  $a$  through  $h$  we find the largest subset of mutually compatible jobs  $\{b, e, h\}$ .

**Definition 1.2: Greedy Algorithm**

A **greedy algorithm** is an algorithm that makes the best choice at each step. I.e., it cares not about the future or big picture, only the immediate benefit, for fast computations.

**Note:** This definition becomes *loose*, as we encounter problems with backtracking or multiple states. As in each state it makes the best choice with the information available.

**Possible Approaches:** Let  $s_j$  and  $f_j$  be the start and finish times of job  $j$ .

- **[Earliest Start Time]:** Consider jobs in ascending order of  $s_j$ .
- **[Earliest Finish Time]:** Consider jobs in ascending order of  $f_j$ .
- **[Shortest Interval]:** Consider jobs in ascending order of  $f_j - s_j$ .
- **[Fewest Conflicts]:** For each  $j$ , count the number of conflicting jobs  $c_j$ .  
Schedule in ascending order of  $c_j$ .

We choose the **Earliest Finish Time** approach:

**Proof 1.1: Greedy Algorithm Earliest Finish Time Correctness**

Let  $i_1, i_2, \dots, i_k$  denote the set of jobs selected by the greedy algorithm.

Let  $j_1, j_2, \dots, j_m$  denote the set of jobs in an optimal solution, with

$i_1 = j_1, i_2 = j_2, \dots, i_r = j_r$  for the largest possible value of  $r$ .

We can swap  $j_{r+1}$  for  $i_{r+1}$  in the optimal schedule, and it will still remain compatible. We repeat swaps until  $r = k$ . It's not possible that  $m > k$  because  $j_{k+1}$  is compatible with  $i_k$ . ■

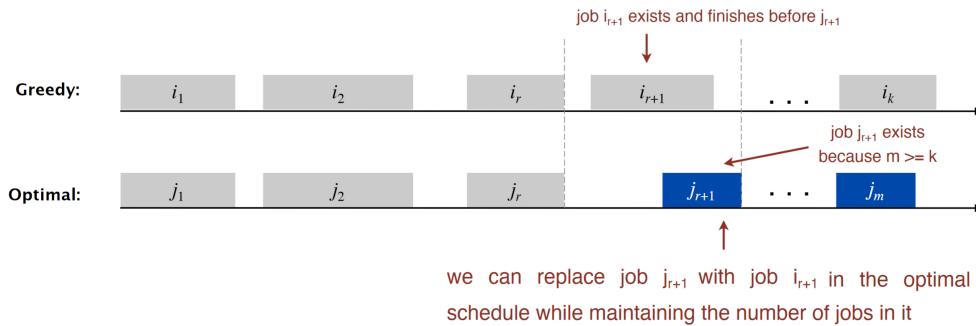


Figure 4.2: Shows that at the first divergence,  $i_{r+1}$  and  $j_{r+1}$ .

**Theorem 1.1: Interval Scheduling & Earliest Finish Time**

Given a set of jobs  $j$  with start and finish times  $s_j$  and  $f_j$ , we can obtain an optimal like solution by scheduling in ascending order of  $f_j$ , choosing the next compatible job.

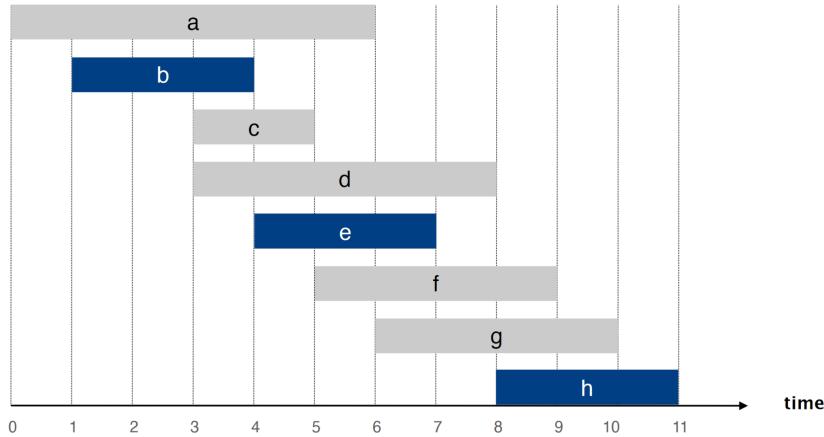


Figure 4.3: Solution to Figure (4.1) using early finish time first, yielding  $\{b, e, h\}$ .

**Function 1.1: EarliestFinishTimeFirst Algorithm - EFT( $s_1, \dots, s_n, f_1, \dots, f_n$ )**

Finds the maximum set of non-overlapping jobs based on earliest finish time.

**Input:** A set of jobs with start times  $s_j$  and finish times  $f_j$ .

**Output:** The maximum set of selected jobs.

```

1 sorted_jobs ← sort( $f_1, \dots, f_n$ ) // sort by finish time
2    $f_{last} \leftarrow -\infty$ ;
3   for each  $j$  in sorted_jobs do
4     if  $f_{last} \leq s_j$  then
5        $S \leftarrow S \cup \{j\}$ ;
6        $f_{last} \leftarrow f_j$ ;
7   end
8 return  $S$ 
```

**Time Complexity:**  $O(n \log n)$  assuming our sorting algorithm is  $O(n \log n)$ . Then we iterate through  $n$  jobs.

**Space Complexity:**  $O(n)$  storing the input of  $n$  jobs.

## 4.2 Interval Partitioning

Interval partitioning generalizes our interval scheduling to multiple resources, allowing them to run in parallel.

### Definition 2.1: Interval Partitioning

Given a schedule of jobs  $j$  with start and finish times  $s_j$  and  $f_j$ . We **partition** jobs into a minimal amount of  $k$  resources such that no two jobs on the same resource overlap.

#### Scenerio: *Class Scheduling*

Say we have  $n$  classes and  $k$  classrooms. What are the minimum number of classrooms needed to schedule all classes?

**Example:** Let  $n = \{a, b, c, \dots, i\}$  be classes with start and finish times. We attempt to find the minimum number of  $k$  classrooms needed to schedule all classes.

(1.)

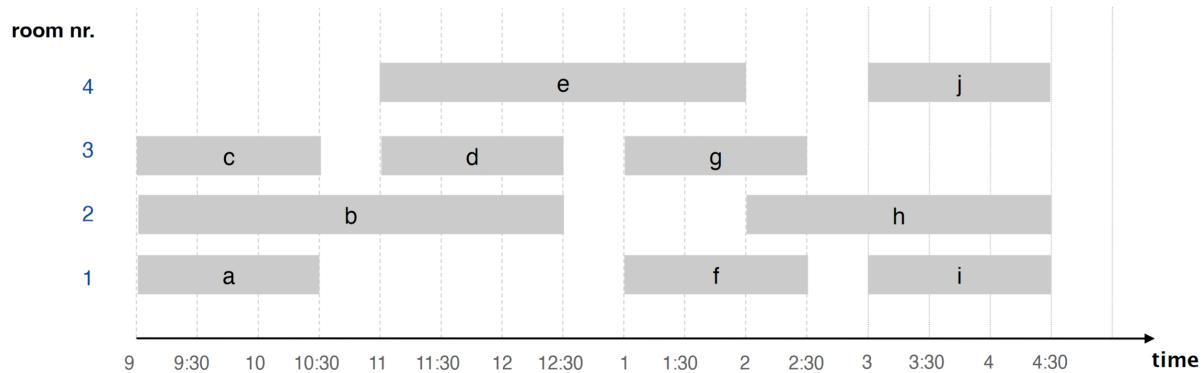


Figure 4.4: Though not optimal, here is a possible schedule where  $k = 4$ .

We strategies and figure out the minimum number of classrooms needed to schedule all classes in the worst-case. We observe in Example (4.2) that  $\{c, b, a\}$  strictly overlap. Moreover, there are at most 3 classes overlapping at any time. Thus, we need at least 3 classrooms.

### Theorem 2.1: Minimality of Interval Partitioning

Given a set of jobs  $j$ ,  $c$  conflicting tasks, and  $k$  resources. We find the optimal  $k$  by  $k = \max(c)$ .

**Possible Approaches:** Let  $s_j$  and  $f_j$  be the start and finish times of job  $j$ .

- [Earliest Start Time]: Consider jobs in ascending order of  $s_j$ .
- [Earliest Finish Time]: Consider jobs in ascending order of  $f_j$ .
- [Shortest Interval]: Consider jobs in ascending order of  $f_j - s_j$ .
- [Fewest Conflicts]: For each  $j$ , count the number of conflicting jobs  $c_j$ .  
Schedule in ascending order of  $c_j$ .

### Theorem 2.2: Interval Partitioning & Earliest Start Time

Given a set of jobs  $j$  with start and finish times  $s_j$  and  $f_j$ , we can obtain an optimal like solution by scheduling in ascending order of  $s_j$ . If two jobs overlap, we allocate a new resource.

### Proof 2.1: Classroom Allocation by Early Start Time First

Let  $d$  be the number of classrooms that the algorithm allocates:

- (i.) Classroom  $d$  is opened because we needed to schedule a lecture, say  $j$ , that is incompatible with all  $d - 1$  other classrooms.
- (ii.) These  $d$  lectures each end after  $s_j$ .
- (iii.) Since we sorted by start time, all these incompatibilities are caused by lectures that start no later than  $s_j$ .

All schedules use  $\geq d$  classrooms. Thus, we have  $d$  lectures overlapping at time  $s_j + \epsilon$ . ■

**Tip:** Though number of conflicts is the optimal number of classrooms, it tells us nothing about how to allocate them. We can use the **Earliest Start Time** as it identifies our next best choice and allocates conflicts as they arise.

**Function 2.1: EarliestStartTimeFirst Algorithm - EST( $j = 1 \dots n : s_j, f_j$ )**

Finds an optimal schedule of lectures based on their earliest start time.

**Input:** A set of lectures with start times  $s_j$  and finish times  $f_j$ .

**Output:** Assignment of lectures to rooms.

```

1  $\mathcal{A} \leftarrow$  empty hash table      //  $\mathcal{A}[k]$  contains the list of lectures assigned to
   room  $k$  sorted_class  $\leftarrow$  sort( $s_1, \dots, s_n$ )           // sort lectures by start time
2 for each  $c$  in sorted_class do
3    $k \leftarrow$  find_compatible_room( $c, \mathcal{A}, Q$ );
4   if  $k$  is not None then
5     |  $\mathcal{A}[k].add(c)$ ;
6   end
7   else
8     |  $d \leftarrow \text{len}(\mathcal{A})$       // highest room id  $\mathcal{A}[d + 1] \leftarrow []$       // open new room
      |  $\mathcal{A}[d + 1].add(c)$ ;
9   end
10 end
11 return  $\mathcal{A}$ 
```

**Time Complexity:**  $O(n \log n)$  assuming our sorting algorithm is  $O(n \log n)$ . Then we iterate through  $n$  jobs.

**Space Complexity:**  $O(n)$  storing the input of  $n$  jobs.

### 4.3 Priority Queues

In this section we will discuss **min-heaps** which will help us sort maintain elements in a sorted data structure.

**Definition 3.1: Balanced Tree**

A **balanced tree** is a tree where the height of the left and right subtrees of every node differ by at most one.

**Tip:** To spot this, observe each level of the tree and see whether after consecutive levels, one branch has more nodes than the other.

Below is an example of a balanced tree and an unbalanced tree:

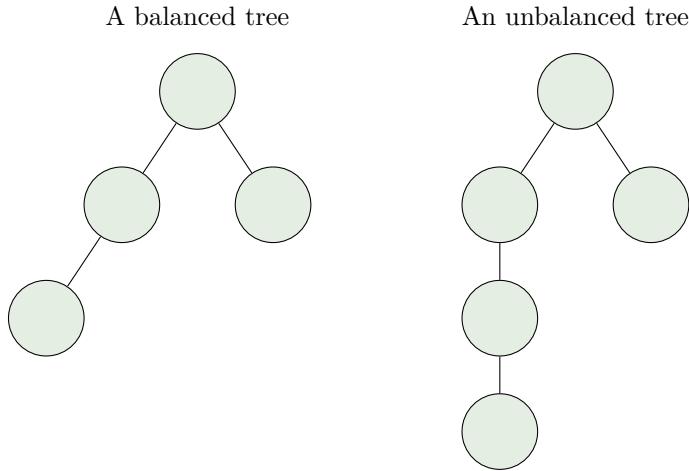


Figure 4.5: Examples of a balanced tree and an unbalanced tree

### Definition 3.2: Binary Search Tree

A **binary tree** is a where each parent node  $p_i$  has at most two children  $c_{left}$  and  $c_{right}$ .  
A **binary search tree** has each child ( $c_{left} > p_i$ ) and ( $c_{right} < p_i$ ).

With  $n$  nodes, there are  $n - 1$  edges.

### Definition 3.3: Heap

A **heap** is a binary tree with the following properties:

- (i.) It is a **complete binary tree** (a binary and balanced tree).
- (ii.) It is a **min-heap** if the parent node is less than its children.
- (iii.) It is a **max-heap** if the parent node is greater than its children.

**Operations:** Suppose we have a heap of  $n$  elements:

- **PEEK:** Return the root.  $O(1)$ ;
- **INSERT:** Add a new element.  $\log(n)$ ;
- **EXTRACT:** Remove the root.  $\log(n)$ ;
- **UPDATE:** Update an element.  $\log(n)$ ;

**Tip:** The difference between a min-heap and a binary search tree, is that  $c_{left} \leq c_{right} \leq p_i$ . That is, the left and right child in a min-heap are not ordered, just less than the parent; Contrary to a binary search tree where the left child is less than the parent and the right child is greater.

We use a min-heap as a data structure to maintain a sorted list as an input.

### Function 3.1: find\_compatible\_room - FCR( $c, A, Q$ )

Finds a compatible room for class  $c$  based on the current room schedule.

**Input:** Class ID  $c$ , current schedule  $A$ , priority queue  $Q$  with room finish times.

**Output:** The room  $k$  compatible with class  $c$  or `None`.

```
// c: class id, A: current schedule of room assignments
// Q: priority queue with room finish times
1  $\langle f_k, k \rangle \leftarrow \text{PEEK\_MIN}(Q)$            // shows lowest (key, value) pair,  $O(1)$ 
2 if  $s_c > f_k$                                 // finish time in room  $k$  then
3 | return  $k$                                   //  $c$  is compatible with room  $k$ 
4 end
5 else
6 | return None;
7 end
```

**Time Complexity:**  $O(n)$  as now we only need to check the minimum finish time in the priority queue.

**Space Complexity:**  $O(n + m)$  if our min-heap is implemented as a hash table.

We can also implement a min-heap for sorting classes as well.

**Function 3.2: EarliestStartTimeFirst Algorithm - EarliestStartTimeFirst( $j = 1 \dots n : s_j, f_j$ )**

Finds an optimal schedule of lectures based on their earliest start time.

**Input:** Start times  $s_j$  and finish times  $f_j$  of classes.

**Output:** Assignment of lectures to rooms.

```

//  $s_j, f_j$ : start and finish times of classes
1  $\mathcal{A} \leftarrow$  empty hash table      //  $\mathcal{A}[k]$  contains the list of courses assigned to
   room  $k$   $Q \leftarrow$  empty priority queue    // contains  $\langle \text{finishTime}, \text{roomId} \rangle$  pairs
   sorted_class  $\leftarrow$  sort( $s_1, \dots, s_n$ )           // sort by start time
2 for each  $c$  in sorted_class do
3    $k \leftarrow \text{find\_compatible\_room}(c, \mathcal{A}, Q)$ ;
4   if  $k$  is not None then
5      $\mathcal{A}[k].\text{add}(c)$ ;
6      $Q.\text{UPDATE-KEY}(\langle f_k, k \rangle, \langle f_c, k \rangle)$           // update finish time of room  $k$ 
7   end
8   else
9      $d \leftarrow \text{len}(\mathcal{A})$       // highest room id  $\mathcal{A}[d+1] \leftarrow []$       // open new room
      $\mathcal{A}[d+1].\text{add}(c)$ ;
10     $Q.\text{INSERT}(\langle f_c, d+1 \rangle)$ ;
11  end
12 end
13 return  $\mathcal{A}$ 
```

**Time Complexity:**  $O(n \log n)$  as inserting into a min heap is  $O(\log n)$  and reading is  $O(1)$ .

**Space Complexity:**  $O(n)$  storing the input of  $n$  classes.

**Theorem 3.1: Heap Array Representation**

A heap  $H$  can be represented by a zero-indexed array  $A$  via:

- (i.) The root is at index 0.
- (ii.) The left child of node  $i$  is at index  $2i + 1$ .
- (iii.) The right child of node  $i$  is at index  $2i + 2$ .

Enabling a **space complexity** of  $O(n)$ .

#### 4.4 Minimizing Lateness