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# CSS.102.1 MATHEMATICAL FOUNDATIONS OF COMPUTER SCIENCE

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CHAPTER 1

# Linear Algebra

# Combinatorics

## 2.1 Twelve Problems: $n$ Balls in $m$ Bins

### Theorem 2.1.1

	$\leq 1$ balls/bin ( $m \geq n$ )	$\geq 1$ balls/bin ( $m \leq n$ )	Unrestricted
Identical Balls, Identical Bins	1	$P(n, m)$	$\sum_{i=1}^m P(n, i)$
Identical Balls, Distinguishable Bins	$\binom{m}{n}$	$\binom{m-1}{n-1}$	$\binom{n+m-1}{m-1}$
Distinguishable Balls, Identical Bins	1	$S_2(n, m)$	$\sum_{i=1}^m S_2(n, i)$
Distinguishable Balls, Distinguishable Bins	$\binom{m}{n} n!$	$S_2(n, m) m!$	$m^n$

*Proof:*

■

## 2.2 Stirling Numbers

### 2.2.1 Stirling Number of Second Kind

#### Definition 2.2.1: Stirling Number of The Second Kind

It is the number of ways to partition the set  $[n]$  into  $m$  nonempty parts.

Clearly if we take the  $n$  balls to be the set  $[n]$  the balls become distinguishable and each partition is bin and the order order of the partition doesn't matter the bins are identical. So the it becomes the number of ways  $n$  distinguishable balls divided into  $m$  identical bins.

Now we will see some recursion relations of the Stirling number of the first kind.

#### Lemma 2.2.1

$$S_2(n, m) = S_2(n-1, m-1) + mS_2(n-1, m)$$

**Combinatorial Proof:** We have the balls  $[n]$ . Then there are two cases. The bin containing ball '1' can have only 1 ball or it can have  $\geq 2$  balls.

For the first case the bin containing ball '1' has only one ball. So the rest of the  $n - 1$  balls are divided into the rest of the  $m - 1$  bins. The number of ways this is done is  $S_2(n - 1, m - 1)$ .

For the second case the bin containing ball '1' has at least 2 balls. In that case apart from the ball '1' all the other balls are filled into  $m$  identical bins where each bin has at least 1 ball. So we can think this scenario in other way that is first we fill bins with all the balls except '1' and then we choose where to put the ball '1'. So the number of ways the balls,  $\{2, 3, \dots, n\}$  i.e.  $n - 1$  distinguishable balls can be divided into  $m$  bins is  $S_2(n - 1, m)$ . Now there are  $m$  choices for the ball '1' to be partnered up. Hence for this case there are  $mS_2(n - 1, m)$  many ways.

Therefore the total number of ways the  $n$  distinguishable balls can be divided into  $m$  bins so that each bin has at least 1 ball is  $S_2(n - 1, m - 1) + mS_2(n - 1, m)$ . Therefore we get  $S_2(n, m) = S_2(n - 1, m - 1) + mS_2(n - 1, m)$ . ■

### Theorem 2.2.2

$$S_2(n + 1, m + 1) = \sum_{i=m}^n \binom{n}{i} S_2(i, m)$$

**Combinatorial Proof:** On the LHS we are counting the number of ways to partition  $[n + 1]$  into  $m + 1$  parts.

For the RHS let's focus on the element  $n + 1$ . So we drop the element from  $[n + 1]$  in the  $(m + 1)^{th}$  part. The  $(m + 1)^{th}$  block can have  $k$  elements from  $[n]$  which are partnered by  $n + 1$  where  $0 \leq k \leq n - m$ . We have  $k \leq n - m$  since all the other  $m$  parts have at least 1 element that leaves us  $n - m$  elements to choose. So there are  $\binom{n}{k}$  ways to choose the  $k$  elements. The remaining  $n - k$  elements are divided into  $m$  parts which can be done in  $S_2(n - k, m)$  many choices. So in total we have  $\sum_{k=0}^{n-m} \binom{n}{k} S_2(n - k, m)$  ways to divide  $[n + 1]$  into  $m + 1$  parts. Therefore we have

$$S_2(n + 1, m + 1) = \sum_{i=0}^{n-m} \binom{n}{i} S_2(n - i, m) = \sum_{i=0}^{n-m} \binom{n}{n-i} S_2(n - i, m) = \sum_{i=m}^n \binom{n}{i} S_2(i, m)$$

■

**Algebraic Proof:** We will prove by Induction.

$$\begin{aligned}
S_2(n+1, m+1) &= S_2(n, m) + (m+1)S_2(n, m+1) \\
&= \sum_{i=m-1}^{n-1} \binom{n-1}{i} S_2(i, m-1) + (m+1) \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) \\
&= \sum_{i=m-1}^{n-1} \binom{n-1}{i} S_2(i, m-1) + m \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) + \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) \\
&= \sum_{i=m}^n \binom{n-1}{i-1} S_2(i-1, m-1) + m \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) + \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) \\
&= \sum_{i=m}^n \binom{n-1}{i-1} S_2(i-1, m-1) + m \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) + \sum_{j=m}^{n-1} \left[ \binom{n}{j} - \binom{n-1}{j-1} \right] S_2(j, m) \\
&= \sum_{i=m}^n \binom{n-1}{i-1} S_2(i-1, m-1) + m \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) + \sum_{j=m}^{n-1} \binom{n}{j} S_2(j, m) - \sum_{j=m}^{n-1} \binom{n-1}{j-1} S_2(j, m) \\
&= \sum_{i=m}^n \binom{n-1}{i-1} S_2(i-1, m-1) + m \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) + \sum_{j=m}^{n-1} \binom{n}{j} S_2(j, m) - \sum_{j=m}^{n-1} \binom{n-1}{j-1} \left[ S_2(j-1, m-1) + m S_2(j-1, m) \right] \\
&= S_2(n-1, m-1) + \sum_{i=m}^{n-1} \binom{n-1}{i-1} S_2(i-1, m-1) + m \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) + \sum_{j=m}^{n-1} \binom{n}{j} S_2(j, m) - \sum_{j=m}^{n-1} \binom{n-1}{j-1} S_2(j-1, m-1) \\
&\quad - m \sum_{j=m}^{n-1} \binom{n-1}{j-1} S_2(j-1, m) \\
&= S_2(n-1, m-1) + m \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) + \sum_{j=m}^{n-1} \binom{n}{j} S_2(j, m) - m \sum_{j=m+1}^{n-1} \binom{n-1}{j-1} S_2(j-1, m) \\
&= S_2(n-1, m-1) + m \sum_{j=m}^{n-1} \binom{n-1}{j} S_2(j, m) + \sum_{j=m}^{n-1} \binom{n}{j} S_2(j, m) - m \sum_{j=m}^{n-2} \binom{n-1}{j} S_2(j, m) \\
&= S_2(n-1, m-1) + m S_2(n-1, m) \sum_{j=m}^{n-1} \binom{n}{j} S_2(j, m) \\
&= S_2(n, m) + \sum_{j=m}^{n-1} \binom{n}{j} S_2(j, m) = \sum_{j=m}^n \binom{n}{j} S_2(j, m)
\end{aligned}$$

■

## 2.2.2 Stirling Number of First Kind

### Definition 2.2.2: Stirling Number of The First Kind

It is the number of permutations of  $[n]$  with exactly  $m$  cycles. The signed version of Stirling number of the first kind is  $(-1)^{n-m} S_1(n, m)$ .

Now we will see some recursion relations of the Stirling number of the first kind.

### Lemma 2.2.3

$$S_1(n, m) = S_1(n-1, m-1) + (n-1)S_1(n-1, m)$$

**Combinatorial Proof:** The LHS is the number of permutations of  $[n]$  into  $m$  cycles by definition.

In the *RHS* we can break the permutations into two different kinds: permutations where  $1 \mapsto 1$  and permutations where  $1 \not\mapsto 1$ . For the permutations  $1 \mapsto 1$  this alone forms a cycle. So the rest of the  $n - 1$  elements have to be permuted into  $m - 1$  cycles. Hence the number of such permutations is  $S_1(n - 1, m - 1)$ .

For permutations where  $1 \not\mapsto 1$  take any permutation  $\sigma$ . We will consider the permutation  $\sigma'$  on the elements  $\{2, \dots, n\}$  where if  $\sigma(k) = 1$  then  $\sigma'(k) = \sigma \circ \sigma(k)$  and otherwise for all  $k \in \{2, \dots, n\}$ ,  $\sigma'(k) = \sigma(k)$ . So  $\sigma'$  is now a permutation of  $\{2, \dots, n\}$ . For all such permutations where  $1 \not\mapsto 1$  we get a new unique permutation  $\sigma'$ . So the number of cycles in  $\sigma$  is same as  $\sigma'$ . Hence it is enough to for now count the number of permutations of  $\{2, \dots, n\}$  into  $m$  cycles is  $S_1(n - 1, m)$ . Now for any such permutation  $\pi$  we can create new  $n - 1$  many permutations where  $\forall i \in \{2, \dots, n\}$  where  $\pi_i(i) = 1$ ,  $\pi_i(1) = \pi(i)$ . In this way for each permutation we get  $n - 1$  new permutations. Hence the number of permutations where  $1 \not\mapsto 1$  is  $(n - 1)S_1(n - 1, m)$ .

Hence total number of permutations of  $[n]$  into  $m$  cycles is  $S_1(n - 1, m - 1) + (n - 1)S_1(n - 1, m)$ . Therefore we get the lemma. ■

#### Lemma 2.2.4

$$S_1(n, m) \binom{m}{k} = \sum_{j=k}^{n+k-m} \binom{n}{j} S_1(j, k) S_1(n - j, m - k)$$

**Combinatorial Proof:** In *LHS*,  $S_1(n, m)$  is the number of permutations on  $[n]$  with exactly  $m$  cycles. Hence  $S_1(n, m) \binom{m}{k}$  is the number of ways to choose  $k$  cycles among the  $m$  cycles from permutations on  $[n]$  with exactly  $m$  cycles. This is same as first constructing the chosen  $k$  cycles with some elements of  $[n]$  and then with the rest of elements construct the rest  $m - k$  cycles.

In *RHS* first we select  $j$  elements for the  $k$  cycles from  $n$  in  $\binom{n}{j}$  ways. Then for the chosen  $j$  elements we create  $k$  cycles in  $S_1(j, k)$  ways. So the number of ways we can create  $k$  cycles by  $j$  elements from  $[n]$  is  $\binom{n}{j} S_1(j, k)$  ways. Now for the rest of the elements we create the rest  $m - k$  cycles which we can do in  $S_1(n - j, m - k)$ . Therefore the number of ways to construct  $k$  cycles and with the rest of the elements construct the remaining  $m - k$  cycles with elements from  $[n]$  is  $\sum_{j=k}^{n+k-m} \binom{n}{j} S_1(j, k) S_1(n - j, m - k)$ . Therefore we have

$$S_1(n, m) \binom{m}{k} = \sum_{j=k}^{n+k-m} \binom{n}{j} S_1(j, k) S_1(n - j, m - k)$$

■

#### Theorem 2.2.5

$$S_1(n + 1, m + 1) = \sum_{j=m}^n \binom{j}{m} S_1(n, j).$$

**Combinatorial Proof:** Consider the permutations on  $[n]$  which has at least  $m$  cycles. So take a permutation  $\sigma$  which has  $j$  cycles where  $m \leq j \leq n$ . So for any cycle consider the smallest element in that cycle to be the leading element. So let the permutation is

$$\sigma = (a_1 \dots a_{\ell_1})(a_{\ell_1+1} \dots a_{\ell_2}) \dots (a_{\ell_{j-1}+1} \dots a_j)$$

Now among these  $j$  cycles we choose  $m$  cycles in  $\binom{j}{m}$  ways. Let the first  $m$  cycles are chosen. Then we create the last  $(m + 1)^{th}$  cycle using the  $n + 1$  in the following way

$$(n + 1 \quad a_{\ell_m} + 1 \quad \dots \quad a_{\ell_{m+1}} \quad a_{\ell_{m+1}} + 1 \quad \dots \quad a_j)$$

Hence for each chosen set of  $m$  cycles we can join the rest of the cycles and  $n + 1$  to get the  $(m + 1)^{th}$  cycle. So now the number of permutations on  $[n]$  with  $j$  cycles is  $S_1(n, j)$ . Then we can choose the  $m$  cycles among  $j$  cycles in  $\binom{j}{m}$  ways. So

the number of permutations on  $[n + 1]$  with  $m + 1$  cycles is  $\sum_{j=m}^n \binom{j}{m} S_1(n, j)$ . Therefore we have

$$S_1(n + 1, m + 1) = \sum_{j=m}^n \binom{j}{m} S_1(n, j)$$

■

**Algebraic Proof:** First we will prove an identity of  $S_1(n + 1, m + 1)$  then we will dive into the prove of this expression. We will show that  $S_1(n + 1, m + 1) = \sum_{k=m}^n \frac{n!}{k!} S_1(k, m)$ . We can use induction on  $n + m + 2$

$$\begin{aligned} S_1(n + 1, m + 1) &= S_1(n, m) + n S_1(n, m + 1) \\ &= S_1(n, m) + n \sum_{k=m}^{n-1} \frac{(n-1)!}{k!} S_1(k, m) \\ &= \frac{n!}{n!} S_1(n, m) + \sum_{k=m}^{n-1} \frac{n!}{k!} S_1(k, m) \\ &= \sum_{k=m}^n \frac{n!}{k!} S_1(k, m) \end{aligned}$$

Now we will prove this inductively.

$$\begin{aligned} \sum_{j=m}^n \binom{j}{m} S_1(n, j) &= \sum_{j=m}^n \sum_{k=m}^{n+m-j} \binom{n}{k} S_1(k, m) S_1(n - k, j - m) && \text{[Using Lemma 2.2.4]} \\ &= \sum_{k=m}^n \binom{n}{k} S_1(k, m) \sum_{j=m}^{n+m-k} S_1(n - k, j - m) \\ &= \sum_{k=m}^n \binom{n}{k} S_1(k, m) \sum_{j=0}^{n-k} S_1(n - k, j) \\ &= \sum_{k=m}^n \binom{n}{k} S_1(k, m) (n - k)! && \left[ \text{Since } \sum_{j=0}^{n-k} S_1(n - k, j) \text{ is number of permutations on } [n - k] \right] \\ &= \sum_{k=m}^n \frac{n!}{k!} S_1(k, m) \\ &= S_1(n + 1, m + 1) \end{aligned}$$

■

Now we will show you a property of the signed Stirling number of the first kind.

#### Theorem 2.2.6

$$S_1(n, m) = \sum_{i=m}^n (-1)^{i-m} \binom{i}{m} S_1(n + 1, i + 1)$$



**Proof:**

$$\begin{aligned}
\sum_{i=m}^n (-1)^{i-m} \binom{i}{m} S_1(n+1, i+1) &= (-1)^{i-m} \binom{i}{m} \sum_{j=i}^n \binom{j}{i} S_1(n, j) \\
&= \sum_{j=m}^n S_1(n, j) \sum_{i=m}^j (-1)^{i-m} \binom{i}{m} \binom{j}{i} \\
&= \sum_{j=m}^n S_1(n, j) \sum_{i=m}^j (-1)^{i-m} \binom{j}{m} \binom{j-m}{i-m} \\
&= \sum_{j=m}^n \binom{j}{m} S_1(n, j) \sum_{i=0}^{j-m} (-1)^i \binom{j-m}{i} \\
&= \sum_{j=m+1}^n \binom{j}{m} S_1(n, j) \underbrace{\sum_{i=0}^{j-m} (-1)^i \binom{j-m}{i}}_{=0} + \binom{m}{m} S_1(n, m) (-1)^0 \binom{0}{0} \\
&= S_1(n, m)
\end{aligned}$$

■

### 2.2.3 Connecting the Two Stirling Numbers

#### Theorem 2.2.7

Let  $S_1$  and  $S_2$  be  $k \times k$  matrix where for any  $n, m \in [k]$  with  $n \geq m$  we have  $(S_1)_{n,m} = (-1)^{n-m} S_1(n, m)$  and  $(S_2)_{n,m} = S_2(n, m)$  and 0 otherwise then  $S_1 S_2 = \mathbb{I}$  i.e.

$$\sum_{i=m}^n (-1)^{n-i} S_1(n, i) S_2(i, m) = \mathbb{I}(n = m)$$

**Proof:** We will induct on  $n + m$ . Then we have

$$\begin{aligned}
\sum_{i=m}^n (-1)^{n-i} S_1(n, i) S_2(i, m) &= \sum_{i=0}^{\infty} (-1)^{n-i} (S_1(n-1, i-1) + (n-1) S_1(n-1, i)) S_2(i, m) \\
&= \sum_{i=0}^{\infty} (-1)^{n-i} S_1(n-1, i-1) S_2(i, m) + (n-1) \sum_{i=0}^{\infty} (-1)^{n-i} S_1(n-1, i) S_2(i, m) \\
&= \sum_{i=0}^{\infty} (-1)^{n-i} S_1(n-1, i-1) [S_2(i-1, m-1) + m S_2(i-1, m)] - (n-1) \mathbb{I}(n-1 = m) \\
&= \sum_{i=0}^{\infty} (-1)^{n-i} S_1(n-1, i-1) S_2(i-1, m-1) + m \sum_{i=0}^{\infty} (-1)^{n-i} S_1(n-1, i-1) S_2(i-1, m) \\
&\quad - (n-1) \mathbb{I}(n-1 = m) \\
&= \mathbb{I}(n = m) + m \mathbb{I}(n-1 = m) - (n-1) \mathbb{I}(n-1 = m) \\
&= \mathbb{I}(n = m) + (m - n + 1) \mathbb{I}(n-1 = m) = \mathbb{I}(n = m)
\end{aligned}$$

■

## 2.3 Inclusion Exclusion Principle

### Theorem 2.3.1 Inclusion-Exclusion Principle

Let  $A_1, \dots, A_n$  be finite sets. Then

$$\left| \bigcup_{i=1}^n A_i \right| = \sum_{J \subseteq [n], J \neq \emptyset} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right|$$

**Proof:** We will prove this using induction on  $n$ .

$$\begin{aligned} \left| \bigcup_{i=1}^n A_i \right| &= \left| \bigcup_{i=1}^{n-1} A_i \right| + |A_n| - \left| \left( \bigcup_{i=1}^{n-1} A_i \right) \cap A_n \right| \\ &= \left| \bigcup_{i=1}^{n-1} A_i \right| + |A_n| - \left| \bigcup_{i=1}^{n-1} (A_i \cap A_n) \right| \\ &= \sum_{J \subseteq [n-1], J \neq \emptyset} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| + |A_n| - \sum_{J \subseteq [n-1], J \neq \emptyset} (-1)^{|J|+1} \left| A_n \cap \left( \bigcap_{j \in J} A_j \right) \right| \\ &= \sum_{J \subseteq [n-1], J \neq \emptyset} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| + |A_n| - \sum_{\substack{J \subseteq [n] \\ J \neq \{n\}, n \in J}} (-1)^{|J|+1} \left| A_n \cap \left( \bigcap_{j \in J - \{n\}} A_j \right) \right| \\ &= \sum_{J \subseteq [n-1], J \neq \emptyset} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| + \sum_{J = \{n\}} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| + \sum_{\substack{J \subseteq [n] \\ J \neq \{n\}, n \in J}} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| \\ &= \sum_{\substack{J \subseteq [n] \\ J \neq \emptyset, n \notin J}} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| + \sum_{J = \{n\}} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| + \sum_{\substack{J \subseteq [n] \\ J \neq \{n\}, n \in J}} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| \\ &= \sum_{J \subseteq [n], J \neq \emptyset} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| \end{aligned}$$

Hence by mathematical induction we have the theorem. ■

### Corollary 2.1

If  $\forall i \in [n], A_i = \{0\}$ . Then

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

**Proof:** Using the Inclusion-Exclusion Principle we have

$$1 = \left| \bigcup_{i=1}^n A_i \right| = \sum_{J \subseteq [n], J \neq \emptyset} (-1)^{|J|+1} \left| \bigcap_{j \in J} A_j \right| = \sum_{J \subseteq [n], J \neq \emptyset} (-1)^{|J|+1} = \sum_{i=1}^n (-1)^{i+1} \binom{n}{i}$$
■

### Corollary 2.3.2

There are  $\sum_{k=0}^n \binom{m}{k} (-1)^k (m-k)^n$  onto functions from  $[n] \rightarrow [m]$

### 2.3.1 Strong Inclusion-Exclusion Principle

**Theorem 2.3.3 Strong Inclusion-Exclusion**

Let  $f : 2^{[n]} \rightarrow \mathbb{R}$ . Define  $g : 2^{[n]} \rightarrow \mathbb{R}$  on a subset  $T \subseteq [n]$  to be as follows

$$g(T) = \sum_{S \subseteq T} f(S) \quad T \subseteq [n]$$

Then

$$f(T) = \sum_{S \subseteq T} (-1)^{|T|-|S|} g(S)$$

### 2.3.2 Mobius Inversion

Now we derive a weak version of Mobius Inversion Theorem directly using [Strong Inclusion Exclusion Principle](#). If  $f$  is a function from all product of primes to  $\mathbb{R}$  and  $g(n) = \sum_{d|n} f(d)$  then we have

$$f(n) = \sum_{d|n} (-1)^{\#\text{divisors of } \left(\frac{n}{d}\right)} g(d) = \sum_{d|n} (-1)^{\#\text{divisors of } (d)} g\left(\frac{n}{d}\right)$$

We define a new function  $\mu : \mathbb{N} \rightarrow \{-1, 0, 1\}$  such that

$$\mu(n) = \begin{cases} 0 & \text{If } n \text{ is not a product of distinct primes} \\ (-1)^{\#\text{prime divisors of } n} & \text{If } n \text{ is a product of distinct primes} \end{cases}$$

So  $\mu$  gets rid of the all the natural numbers  $n$  which is not a product of distinct primes. So now we have the Mobius Inversion Theorem

**Theorem 2.3.4 Mobius Inversion**

Let  $f : \mathbb{N} \rightarrow \mathbb{R}$  and define  $g : \mathbb{N} \rightarrow \mathbb{R}$  such that  $g(n) = \sum_{d|n} f(d)$  then if the function  $\mu : \mathbb{N} \rightarrow \{-1, 0, 1\}$  is defined as above then we have

$$f(n) = \sum_{d|n} \mu(d) g\left(\frac{n}{d}\right)$$

### 2.3.3 Euler Totient Function

**Definition 2.1: Euler Totient Function**

Euler Totient Function,  $\phi : \mathbb{N} \rightarrow \mathbb{N}$ ,  $\phi(n)$  is the number of integers  $m \leq n$  such that  $\gcd(m, n) = 1$ .

**Lemma 2.3.5**

For any  $n \in \mathbb{N}$ ,

$$n = \sum_{d|n} \phi(d)$$

**Proof:** Consider the list of numbers  $S = \left\{\frac{1}{n}, \frac{2}{n}, \dots, \frac{n}{n}\right\}$ . If we express every number in  $S$  as simplified form i.e.  $\frac{p}{q}$  form where  $\gcd(p, q) = 1$ . Then the denominators are all the divisors of  $n$ .

Then for any  $k \in [n]$  we have

$$\frac{k}{n} = \frac{\frac{k}{\gcd(k, n)}}{\frac{n}{\gcd(k, n)}}$$

Denote  $d_k := \frac{n}{\gcd(k,n)}$  then  $d_k$  is a factor of  $n$ . And since  $\gcd\left(\frac{k}{\gcd(k,n)}, \frac{n}{\gcd(k,n)}\right) = 1$  we have  $\frac{k}{\gcd(k,n)} \in \mathbb{Z}_{d_k}^*$ . Let  $k \in \mathbb{Z}_d^*$  then suppose  $l$  is such that  $d \times l = n$  then the fraction  $\frac{k}{d} = \frac{k \times l}{n} \in S$  and its simplified form is in fact  $\frac{k}{d}$ .

Hence for any  $d \mid n$ , the number of fractions with denominator  $d$  is  $\phi(d)$ , since for all such fractions the numerators are the elements of  $\mathbb{Z}_{d_k}^*$ . Therefore we have  $\sum_{d \mid n} \phi(d) = n$ . ■

**Alternate Proof:**

$$n = \sum_{i=1}^n 1 = \sum_{d \mid n} \sum_{\substack{i \leq n, \\ \gcd(i,n)=d}} 1 = \sum_{d \mid n} \sum_{\substack{d \mid i, i \leq n, \\ \gcd\left(\frac{i}{d}, \frac{n}{d}\right)=1}} 1 = \sum_{d \mid n} \sum_{\substack{j \leq \frac{n}{d}, \\ \gcd\left(\frac{n}{d}, j\right)=1}} 1 = \sum_{d \mid n} \phi\left(\frac{n}{d}\right) = \sum_{d \mid n} \phi(d)$$

Since  $n = \sum_{d \mid n} \phi(d)$  this is already in the form  $g(n) = \sum_{d \mid n} f(d)$ . Hence take  $g: \mathbb{N} \rightarrow \mathbb{R}$  to be identity function and take  $f$  to be the Euler Totient function. Then by [Mobius Inversion](#) we have

$$\phi(n) = \sum_{d \mid n} \mu(d) g\left(\frac{n}{d}\right) = \sum_{d \mid n} \mu(d) \frac{n}{d} \implies \frac{\phi(n)}{n} = \sum_{d \mid n} \frac{\mu(d)}{d}$$

## 2.4 Generating Function

### Question 2.4.1

What is the number of non-negative solutions of  $x_1 + x_2 + x_3 + x_4 = 5$  for which  $x_1 + x_2$  is even?

**Solution:**  $x_1 + x_2$  is even. So it can be 0 or 2 or 4. In that case  $x_3 + x_4$  can be 5 or 3 or 1 respectively. For any  $k$ ,  $x + y = k$  in  $k + 1$  ways where  $x, y$  are non-negative. Then the total number of solutions is  $1 \times 6 + 3 \times 4 + 5 \times 2 = 28$ .

Another way of solving this is consider the power series

$$A(x) = 1 + 3x^2 + 5x^4 + \dots = \sum_{i=0}^{\infty} a_i x^i \quad B(x) = 1 + 2x + 3x^2 + \dots = \sum_{i=0}^{\infty} b_i x^i$$

Where

$$a_i = \begin{cases} \text{\#solutions to } x_1 + x_2 = i & \text{when } i \text{ is even} \\ 0 & \text{when } i \text{ is odd} \end{cases}, \quad b_i = \text{\#solutions to } x_1 + x_2 = i$$

Then for  $A \cdot B = C = \sum_{i=0}^{\infty} c_i x^i$ ,  $c_i = \text{\#solutions to } x_1 + x_2 + x_3 + x_4 = i$  where  $x_1 + x_2$  is even. ■

### Question 2.4.2

What is the number of subsets of  $[n]$  of size  $k$ ?

**Solution:** Suppose there are  $n$  variables  $x_1, \dots, x_n$ . For each subset  $S \subseteq [n]$  where  $|S| = k$ , we assign  $x_i = 1$  if  $i \in S$  and otherwise assign  $x_i = 0$ . Hence the number of subsets of  $[n]$  of size  $k$  is same as the number of solutions of  $\sum_{i=1}^n x_i = k$ .

Consider the following generating function

$$(1+x)^n = \sum_{i=0}^n \binom{n}{i} x^i = \sum_{i=0}^n a_i x^i$$

Here for each  $i$ ,  $a_i = \# \text{solutions for } \sum_{i=1}^n x_i = k$ . Therefore number of subsets of  $[n]$  of size  $k$  is  $\binom{n}{k}$ . ■

### Question 2.4.3

How many partitions of  $n$  are there?

**Solution:** We can find a nice generating function for number of partitions of  $n$ . We have

$$\sum_{n \geq 0} P(n)x^n = \prod_{r=1}^{\infty} \sum_{i=0}^{\infty} x^{i \cdot r}$$

For each  $r \geq 1$  for any  $i \geq 0$  think of  $x^{i \cdot r}$  as the number of  $r$ 's in a partition of  $n$  is  $i$ . So if  $P$  is a partition of  $n$  then suppose  $n_i$  be the number of  $i$ 's in  $P$ . Hence we have  $\sum_{i=1}^n i \cdot n_i = n$  Then the corresponding term  $x^n$  is generated by the  $\prod_{i=1}^n x^{i \cdot n_i}$  where  $x^{i \cdot n_i}$  comes from the  $\sum_{j=0}^{\infty} x^{j \cdot n_i}$ . Hence

$$\sum_{n \geq 0} P(n)x^n = \prod_{r=1}^{\infty} \sum_{i=0}^{\infty} x^{i \cdot r} = \prod_{r=1}^{\infty} \frac{1}{1 - x^r}$$

## 2.4.1 Well Formed Parenthesis and Catalan Number

### Definition 2.2: Well Formed Parenthesis

A sequence of parenthesis is well formed if  $\#( = \#)$  and any prefix has at least as many  $($  as  $)$ .

Now consider for any  $i \geq 0$ ,

$a_i = \# \text{Well formed parenthesis of length } 2i$

$b_i = \# \text{Well formed parenthesis such that the first matches the last and length } 2i$

### Definition 2.3: Catalan Number

The  $n^{\text{th}}$  Catalan Number is the number of well formed parenthesis of length  $2n$ , i.e.  $a_i$ .

**Observation 1.**  $b_n = a_{n-1}$ .

Since for  $b_n$  the first matches with the last. So the internal  $2(n-1)$  parenthesis forms a well formed parenthesis and that can be in  $a_{n-1}$  ways.

**Observation 2.**  $a_n = \sum_{i=1}^n b_i a_{n-i} = \sum_{i=1}^n a_{i-1} a_{n-i}$ .

Since there are  $2n$  parenthesis the first  $($  is matched with a  $)$  at any of the  $n$ 's since inside them all the parenthesis are forms well formed parenthesis. Hence we consider each case where the first  $($  matched with  $i^{\text{th}}$  differently. If the first  $($  is matched with  $i^{\text{th}}$  then inside them there is  $2(i-1)$  length well formed parenthesis and we can think of this case as  $b_i$  and the rest  $2n-2i$  many parenthesis forms all possible well formed parenthesis which can be done in  $a_{n-i}$  ways. So the number of ways the first  $($  is matched with  $i^{\text{th}}$  is  $b_i a_{n-i}$  ways.

Now define the power series  $A(x) = \sum_{i \geq 0} a_i x^i$ . Then we have

$$A^2(x) = \sum_{i \geq 0} \left( \sum_{j=0}^i a_j a_{i-j} \right) x^i$$

This is almost in the form  $\sum_{i=1}^n a_{i-1}a_{n-i}$  for coefficient of  $x^i$ . So we do the following

$$xA^2(x) = x \sum_{i \geq 0} \left( \sum_{j=0}^i a_j a_{i-j} \right) x^i = \sum_{i \geq 0} \left( \sum_{j=0}^i a_j a_{i-j} \right) x^{i+1} = \sum_{i \geq 0} \left( \sum_{j=1}^{i+1} a_{j-1} a_{i+1-j} \right) x^{i+1} = \sum_{i \geq 0} a_{i+1} x^{i+1} = A(x) - 1$$

Hence we get a quadratic equation for  $A(x)$  which is  $A^2(x)x - A(x) + 1 = 0$ . Therefore

$$A(x) = \frac{1 \pm \sqrt{1-4x}}{2x}$$

Now

$$\sqrt{1-4x} = 1 + \frac{1}{2}(-4x) + \frac{\frac{1}{2} \times (\frac{1}{2} - 1)}{2!}(-4x)^2 + \frac{\frac{1}{2}(\frac{1}{2} - 1)(\frac{1}{2} - 2)}{3!}(-4x)^3 + \dots = \sum_{i \geq 0} \binom{\frac{1}{2}}{i} (-4x)^i$$

Therefore

$$\frac{1 + \sqrt{1-4x}}{2x} = \frac{1}{x} + \sum_{i \geq 1} 2 \binom{\frac{1}{2}}{i} (-1)^i (4x)^{i-1}$$

Now as  $x \rightarrow 0$  we have  $\frac{1 + \sqrt{1-4x}}{2x}$  does not exist but we have

$$\frac{1 - \sqrt{1-4x}}{2x} = \sum_{i \geq 1} 2 \binom{\frac{1}{2}}{i} (-4x)^{i-1} = \sum_{i \geq 0} 2 \binom{\frac{1}{2}}{i+1} (-4x)^i \quad \text{and} \quad \lim_{x \rightarrow 0} \sum_{i \geq 0} 2 \binom{\frac{1}{2}}{i+1} (-4x)^i = 2 \binom{\frac{1}{2}}{0+1} (-4)^0 = 2 \frac{1}{2} = 1 = a_0$$

Therefore we have

$$A(x) = \frac{1 - \sqrt{1-4x}}{2x} = \sum_{i \geq 0} 2 \binom{\frac{1}{2}}{i+1} (-4x)^i$$

Now

$$a_i = 2 \binom{\frac{1}{2}}{i+1} = 2 \times (-4)^i \frac{\prod_{j=0}^i (\frac{1}{2} - j)}{(i+1)!} = \frac{2 \times (-4)^i \prod_{j=0}^i (1-2j)}{2^{i+1} (i+1)!} = 2^i \frac{\prod_{j=0}^i (2j-1)}{(i+1)!} = \frac{1}{i+1} \binom{2i}{i}$$

Hence the  $n^{\text{th}}$  Catalan Number is  $\frac{1}{n+1} \binom{2n}{n}$ .

## 2.4.2 Generating Function of Stirling Number of First Kind

Take the generating function for  $S_1(m, m)$  to be  $\sum_{m=0}^n S_1(n, m)x^m$ . Then we have the following theorem

### Theorem 2.4.1

$$\sum_{m=0}^n S_1(n, m)x^m = \prod_{m=0}^{n-1} (x+m)$$

**Proof:** We will prove this by proving that the coefficients of  $RHS$  follows the recursion relation [Lemma 2.2.3](#) and also the initial conditions are same as Stirling Number of the First Kind. For  $n = 1$ , we have

$$S_1(1, 0) + S_1(1, 1)x = 0 + x$$

Hence it is satisfied. For any  $n$ ,  $S(n, n) = 1$  and the coefficient of  $x^n$  in  $\prod_{m=0}^{n-1} (x+m)$  is also 1. Therefore the initial conditions are satisfied. Now we will show that [Lemma 2.2.3](#) is followed. We will use induction on  $n$ . The base case is

already followed.

$$\begin{aligned}
 \prod_{m=1}^n (x + m - 1) &= x \prod_{m=1}^{n-1} (x + j - 1) + (n - 1) \prod_{j=1}^{n-1} (x + j - 1) \\
 &= x \sum_{m=0}^{n-1} S_1(n-1, m) x^m + (n-1) \sum_{m=0}^{n-1} S_1(n-1, m) x^m && \text{[Induction Hypothesis]} \\
 &= \sum_{m=1}^n S_1(n-1, m-1) x^m + (n-1) \sum_{m=0}^n S_1(n-1, m) x^m \\
 &= \sum_{m=0}^n S_1(n-1, m-1) x^m + (n-1) \sum_{m=0}^n S_1(n-1, m) x^m \\
 &= \sum_{m=0}^n (S_1(n-1, m-1) + (n-1) S_1(n-1, m)) x^m = \sum_{m=0}^n S_1(n, m) x^m
 \end{aligned}$$

■

### 2.4.3 Exponential Generating Function