

Combinatorics

Discrete Math, Spring 2025

Konstantin Chukharev

Combinatorics

Introduction to Combinatorics

Definition 1: Combinatorics is the branch of discrete mathematics that deals with *counting*, *arranging*, and analyzing *discrete structures*.

Three basic problems of Combinatorics:

1. Existence: *Is there at least one arrangement of a particular kind?*
2. Counting: *How many arrangements are there?*
3. Optimization: *Which one is best according to some criteria?*

Discrete structures

- Graphs, sets, multisets, sequences, patterns, coverings, partitions...

Enumeration

- Permutations, combinations, inclusion/exclusion, generating functions, recurrence relations...

Algorithms and optimization

- Sorting, eulerian circuits, hamiltonian cycles, planarity testing, graph coloring, spanning trees, shortest paths, network flows, bipartite matchings, chain partitions...

Discrete Structures

We investigate the *building blocks* of combinatorics:

- Sets and multisets
- Sequences and strings
- Arrangements
- Graphs, networks, trees
- Posets and lattices
- Partitions
- Patterns, coverings, designs, configurations
- Schedules, assignments, distributions

Used in data modeling, logic, cryptography, and the design of data structures.

Enumerative Combinatorics

We learn how to count *without explicit listing*:

- Permutations and combinations
- Inclusion–Exclusion Principle
- Set partitions, integer partitions, Stirling numbers, Catalan numbers
- Recurrence relations
- Generating functions

Used in probability theory, complexity theory, coding theory, computational biology.

Algorithmic and Optimization Methods

Combinatorics powers *algorithm design* and complexity analysis:

- Sorting
- Searching
- Eulerian paths and Hamiltonian cycles
- Planarity, colorings, cliques, coverings
- Spanning trees
- Shortest paths
- Network flows
- Bipartite matchings
- Dilworth's theorem, chain and antichain partitions

Used in logistics, scheduling, routing, and complexity optimization.

Basic Counting Principles

Basic Counting Rules

PRODUCT RULE: If something can happen in n_1 ways, *and* no matter how the first thing happens, a second thing can happen in n_2 ways, then the two things *together* can happen in $n_1 \cdot n_2$ ways.

SUM RULE: If one event can occur in n_1 ways and a second event in n_2 (different) ways, then there are $n_1 + n_2$ ways in which *either* the first event *or* the second event can occur (*but not both*).

Addition Principle

Definition 2: We say a finite set S is *partitioned* into *parts* S_1, \dots, S_k if the parts are pairwise disjoint and their union is S . In other words, $S_i \cap S_j = \emptyset$ for $i \neq j$ and $S_1 \cup S_2 \cup \dots \cup S_k = S$. In that case:

$$|S| = |S_1| + |S_2| + \dots + |S_k|$$

Example: Let S be the set of students attending the combinatorics lecture. It can be partitioned into parts S_1 and S_2 where

S_1 = set of students that like easy examples.

S_2 = set of students that don't like easy examples.

If $|S_1| = 22$ and $|S_2| = 8$, then we can conclude $|S| = |S_1| + |S_2| = 30$.

Multiplication Principle

Definition 3: If S is a finite set that is the *product* of S_1, \dots, S_k , that is, $S = S_1 \times \dots \times S_k$, then

$$|S| = |S_1| \times \dots \times |S_k|$$

Example: TODO: example with car plates

Subtraction Principle

Definition 4: Let S be a subset of a finite set T . We define the *complement* of S as $\overline{S} = T \setminus S$. Then

$$|\overline{S}| = |T| - |S|$$

Example: If T is the set of students studying at KIT and S the set of students studying neither math nor computer science. If we know $|T| = 23905$ and $|S| = 20178$, then we can compute the number $|S|$ of students studying either math or computer science:

$$|S| = |T| - |\overline{S}| = 23905 - 20178 = 3727$$

Bijection Principle

Definition 5: If S and T are sets, then

$$|S| = |T| \iff \text{there exists a bijection between } S \text{ and } T$$

Example: Let S be the set of students attending the combinatorics lecture and T the set of homework submissions (unique per student) for the first problem sheet. If the number of students and the number of submissions coincide, then there is a bijection between students and submissions.

Note: The bijection principle works both for *finite* and *infinite* sets.

Pigeonhole Principle

Definition 6: Let S_1, \dots, S_k be finite sets that are pairwise disjoint and $|S_1| + |S_2| + \dots + |S_k| = n$.

$$\exists i \in \{1, \dots, k\} : |S_i| \geq \left\lfloor \frac{n}{k} \right\rfloor \quad \text{and} \quad \exists j \in \{1, \dots, k\} : |S_j| \leq \left\lceil \frac{n}{k} \right\rceil$$

Example: Assume there are 5 holes in the wall where pigeons nest. Say there is a set S_i of pigeons nesting in hole i . Assume there are $n = 17$ pigeons in total. Then we know:

- There is some hole with at least $d = 4$ pigeons.
- There is some hole with at most $b = 3$ pigeons.

Double Counting

If we count the same quantity in *two different ways*, then this gives us a (perhaps non-trivial) identity.

Example (Handshaking Lemma): Assume there are n people at a party and everybody will shake hands with everybody else. How many handshakes will occur? We count this number in two ways:

1. Every person shakes $n - 1$ hands and there are n people. However, two people are involved in a handshake so if we just multiply $n \cdot (n - 1)$, then every handshake is counted twice. The total number of handshakes is therefore $\frac{n \cdot (n-1)}{2}$.
2. We number the people from 1 to n . To avoid counting a handshake twice, we count for person i only the handshakes with persons of lower numbers. Then the total number of handshakes is:

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

$$\text{The identity we obtain is therefore: } \sum_{i=1}^{n-1} i = \frac{n \cdot (n - 1)}{2}$$

Arrangements, Permutations, Combinations

Ordered Arrangements

Definition 7: Denote by $[n] = \{1, \dots, n\}$ the set of natural numbers from 1 to n .

Hereinafter, let X be a finite set.

Definition 8: An *ordered arrangement* of n elements of X is a *map* $s : [n] \rightarrow X$.

- Here, $[n]$ is the *domain* of s , and $s(i)$ is the *image* of $i \in [n]$ under s .
- The set $\{x \in X \mid s(i) = x \text{ for some } i \in [n]\}$ is the *range* of s .

Other common names for ordered arrangements are:

- *string* (or *word*), e.g. “Banana”
- *sequence*, e.g. “0815422372”
- *tuple*, e.g. $(3, 5, 2, 5, 8)$

Example:

i	1	2	3	4	5	6	7
$s(i)$	🦀	🍞	🍞	罐头	🍞	🦀	罐头

Permutations

Definition 9: A *permutation* of X is a *bijective* map $\pi : [n] \rightarrow X$.

Usually, $X = [n]$, and the set of all permutations of $[n]$ is denoted by S_n .

Example:

i	1	2	3	4	5	6	7
$\pi(i)$	2	7	1	3	5	4	6

Definition 10: *k-permutation* of X is an ordered arrangement of k *distinct* elements of X , that is, an *injective* map $\pi : [k] \rightarrow X$.

The set of all k -permutations of $X = [n]$ is denoted by $P(n, k)$. In particular, $S_n = P(n, n)$.

TODO: circular permutations

Counting Permutations

Theorem 1: For any natural numbers $0 \leq k \leq n$, we have

$$|P(n, k)| = n \cdot (n - 1) \cdot \dots \cdot (n - k + 1) = \frac{n!}{(n - k)!}$$

This formula is also called the *falling factorial* and denoted n^k or $(n)_k$.

Proof: A permutation is an injective map $\pi : [k] \rightarrow [n]$. We count the number of ways to pick such a map, picking the images one after the other. There are n ways to choose $\pi(1)$. Given a value for $\pi(1)$, there are $(n - 1)$ ways to choose $\pi(2)$ (since we may not choose $\pi(1)$ again). Continuing like this, there are $(n - i + 1)$ ways to pick $\pi(i)$, and the last value we pick is $\pi(k)$ with $(n - k + 1)$ possibilities.

Every k -permutation can be constructed like this in *exactly one way*. The total number of k -permutations is therefore given as the product:

$$|P(n, k)| = n \cdot (n - 1) \cdot \dots \cdot (n - k + 1) = \frac{n!}{(n - k)!}$$

□

Counting Circular Permutations

Theorem 2: For any natural numbers $0 \leq k \leq n$, we have

$$|P_c(n, k)| = \frac{n!}{k \cdot (n - k)!}$$

Proof: We doubly count $P(n, k)$:

1. $|P(n, k)| = \frac{n!}{(n-k)!}$ which we proved before.
2. $|P(n, k)| = |P_c(n, k)| \cdot k$ because every equivalence class in $P_c(n, k)$ contains k permutations from $P(n, k)$ since there are k ways to rotate a k -permutation.

From this we get $\frac{n!}{(n-k)!} = |P_c(n, k)| \cdot k$, which implies $|P_c(n, k)| = \frac{n!}{k \cdot (n - k)!}$. □

Unordered Arrangements

Definition 11: An *unordered arrangement* of k elements of X is a *multiset* $S = \langle X, r \rangle$ of size k .

In a multiset, X is the set of *types*, and for each type $x \in X$, r_x is its *repetition number*.

Example: Let $X = \{ \text{👉}, \text{🐋}, \text{🐱}, \text{🂱}, \text{🌵} \}$.

- An unordered arrangement of 7 elements could be $S = \{ \text{👉}, \text{👉}, \text{🐋}, \text{🐋}, \text{🐱}, \text{🐱}, \text{🐱}, \text{🌵} \}^*$.
- The same multiset could be written as $S = \{2 \text{👉}, 1 \text{🐋}, 3 \text{🐱}, 0 \text{🂱}, 1 \text{🌵}\}$.

Subsets

The most important special case of unordered arrangements is where all repetitions are 1, that is, $r_x = 1$ for all $x \in X$. Then S is simply a *subset* of X , denoted $S \subseteq X$.

Definition 12: A *k-combination* of X is an unordered arrangement of k *distinct* elements of X .

Note: The more standard term is *subset*. The term “combination” is only used to emphasize the selection process.

The set of all k -subsets of X is denoted $\binom{X}{k} = \{A \subseteq X \mid |A| = k\}$. If $|X| = n$, then

$$\binom{n}{k} := \left| \binom{X}{k} \right|$$

Example: The set of edges in a simple undirected graph consists of 2-subsets of its vertices: $E \subseteq \binom{V}{2}$.

Counting k -Combinations

Theorem 3: For $0 \leq k \leq n$, we have

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

Proof: $|P(n, k)| = \frac{n!}{(n - k)!} = \binom{n}{k} \cdot k!$

□

Multisets

Multiset

Definition 13: A *multiset* is a modification of the concept of a set that allows for *repetitions* of its elements. Formally, it is denoted as a pair $M = \langle X, r \rangle$, where X is the *groundset* (the set of *types*) and $r : X \rightarrow \mathbb{N}_0$ is the *multiplicity function*.

Example: When the multiset is defined by enumeration, it is advisable to use the notation with the star:

$$M = \{a, b, a, a, b\}^* = \{3 \cdot a, 2 \cdot b\} \quad X = \{a, b\} \quad r_a = 3, r_b = 2$$

Example: Prime factorization of a natural number n is a multiset, e.g. $120 = 2^3 \cdot 3^1 \cdot 5^1$.

k-Combinations of a Multiset

Definition 14: Let X be a finite set of types, and let $M = \langle X, r \rangle$ be a finite multiset with repetition numbers $r_1, \dots, r_{|X|}$. A *k-combination of M* is a multiset $S = \langle X, s \rangle$ with types in X and repetition numbers $s_1, \dots, s_{|X|}$ such that $s_i \leq r_i$ for all $1 \leq i \leq |X|$, and $\sum_{i=1}^{|X|} s_i = k$.

Example: Consider $M = \{2\text{ Beaver}, 1\text{ Soda}, 3\text{ Watermelon}, 1\text{ Diamond}\}$.

- $T = \{1\text{ Beaver}, 2\text{ Watermelon}\}$ is a 3-combination of M .
- $T' = \{3\text{ Diamond}\}$ is not.

Counting k-combinations of a multiset is not as simple as it might seem...

k-Permutations of a Multiset

Definition 15: Let M be a finite multiset with set of types X . A *k-permutation of M* is an ordered arrangement of k elements of M where different orderings of elements of the same type are *not distinguished*. This is an ordered multiset with types in X and repetition numbers $s_1, \dots, s_{|X|}$ such that $s_i \leq r_i$ for all $1 \leq i \leq |X|$, and $\sum_{i=1}^{|X|} s_i = k$.

Note: There might be several elements of the same type compared to a permutation of a set (where each repetition number equals 1).

Example: Let $M = \{2\text{🐦}, 1\text{🥤}, 3\text{🍉}, 1\text{💎}\}$, then $T = (\text{💎}, \text{🍉}, \text{🍉}, \text{🐦})$ is a 4-permutation of multiset M .

Binomial Theorem

Theorem 4: The expansion of any non-negative integer power n of the binomial $(x + y)$ is a sum

$$(x + y)^n = \sum_{k=0}^n \binom{n}{k} \cdot x^k \cdot y^{n-k}$$

where each $\binom{n}{k}$ is a positive integer known as a *binomial coefficient*, defined as

$$\binom{n}{k} = \frac{n!}{k! \cdot (n - k)!} = \frac{n \cdot (n - 1) \cdot (n - 2) \cdot \dots \cdot (n - k + 1)}{k \cdot (k - 1) \cdot (k - 2) \cdot \dots \cdot 2 \cdot 1}$$

Multinomial Theorem

Theorem 5: The generalization of the binomial theorem:

$$(x_1 + \dots + x_r)^n = \sum_{\substack{0 \leq k_1, \dots, k_r \leq n \\ k_1 + \dots + k_r = n}} \binom{n}{k_1, \dots, k_r} \cdot x_1^{k_1} \cdot \dots \cdot x_r^{k_r}$$

Multinomial coefficients are defined as

$$\binom{n}{k_1, \dots, k_r} = \frac{n!}{k_1! \cdot \dots \cdot k_r!}$$

Note: Binomial coefficients are special cases of multinomial coefficients ($r = 2$):

$$\binom{n}{k} = \binom{n}{k_1, k_2} = \binom{n}{k, n-k} = \frac{n!}{k! \cdot (n-k)!}$$

Proof: TODO

□

Permutations of a Multiset

Theorem 6: Let S be a finite multiset with k different types and repetition numbers r_1, \dots, r_k . Let the size of S be $n = r_1 + \dots + r_k$. Then the number of n -permutations of S equals

$$\binom{n}{r_1, \dots, r_k}$$

Proof: In an n -permutation there are n positions that need to be assigned a type.

First, choose the r_1 positions for the first type, there are $\binom{n}{r_1}$ ways to do so. Then, assign r_2 positions for the second type, out of the $(n - r_1)$ positions that are still available, there are $\binom{n-r_1}{r_2}$ ways to do so. Continue for all k types. The total number of choices will be:

$$\binom{n}{r_1} \cdot \binom{n-r_1}{r_2} \cdot \dots \cdot \binom{n-r_1-r_2-\dots-r_{k-1}}{r_k} = \binom{n}{r_1, \dots, r_k}$$

□

k-Combinations of an *Infinite Multiset*

Example: Suppose you have a *sufficiently large* amount of each type of fruit (🍌, 🍎, 🍐) in the supermarket, and you want to buy *two* fruits. How many choices do you have?

There are exactly *six* combinations: {🍌, 🍌}, {🍌, 🍎}, {🍌, 🍐}, {🍎, 🍎}, {🍎, 🍐}, {🍐, 🍐}.

Note that your selection is *not ordered*, so {🍐, 🍎} and {🍎, 🍐} are considered the *same* choice.

***k*-Combinations of an *Infinite Multiset* [2]**

Theorem 7: Let $k, s \in \mathbb{N}$ and let S be a multiset with s types and large repetition numbers (each r_1, \dots, r_s is at least k), then the number of k -combinations of S equals

$$\binom{k+s-1}{k} = \binom{k+s-1}{s-1}$$

- Let $k = 5$ (as an example). Consider a 5-combination of S : { , , , , }.
 - Reorder and group: { | | }.
 - Convert to *dots* and *bars*: $\bullet\bullet | \bullet | \bullet\bullet$
 - Represent as a 2-type multiset: $M = \{ k \cdot \bullet, (s - 1) \cdot | \}$
 - Observe: each *permutation* of k dots and $(s - 1)$ bars corresponds *uniquely* to a *k -combination* of S .
 - Permute the 2-type multiset: $\binom{k+s-1}{k,s-1}$ ways, by Theorem 5.

This method is also known as *Stars and Bars*.

1

Compositions

Weak Compositions

Definition 16: A *weak composition* of a non-negative integer $k \geq 0$ into s parts is a *solution* to the equation $b_1 + \dots + b_s = k$, where each $b_i \geq 0$.

Example: Let $k = 5$, $s = 3$. Possible non-negative integer solutions for $b_1 + b_2 + b_3 = 5$ are:

- $(b_1, b_2, b_3) = (1, 1, 3)$
- $(b_1, b_2, b_3) = (1, 3, 1)$
- $(b_1, b_2, b_3) = (2, 0, 3)$
- $(b_1, b_2, b_3) = (0, 5, 0)$
- ... (total 21 solutions)

Note: If M is a multiset over groundset $\{1, \dots, s\}$ with all multiplicities infinite ($r_i = \infty$), then for $k \geq 0$, the number of sub-multisets of M of size k is exactly the number of weak compositions of k into s parts.

Counting Weak Compositions

Theorem 8: There are $\binom{k+s-1}{k, s-1}$ *weak compositions* of $k > 0$ into s parts.

Proof: Observe that $k = \overbrace{1+1}^{b_1} + \underbrace{\dots}_{b_i} + \overbrace{1+1}^{b_s}$ k ones

Use the *stars-and-bars* method to count the number of s groups composed of k “ones”. □

Example: Let $k = 3$. There are $\binom{3+3-1}{3, 3-1} = \binom{5}{3} = \binom{5}{2} = 10$ ways to decompose $k = 3$ into $s = 3$ parts:

$$\begin{aligned} k = 3 &= \\ &= 0 + 1 + 2 = 0 + 2 + 1 \\ &= 1 + 0 + 2 = 1 + 2 + 0 = 1 + 1 + 1 \\ &= 2 + 0 + 1 = 2 + 1 + 0 \\ &= 3 + 0 + 0 = 0 + 3 + 0 = 0 + 0 + 3 \end{aligned}$$

Compositions

Definition 17: A *composition* of a positive integer $k \geq 1$ into s *positive* parts is a *solution* to the equation $b_1 + \dots + b_s = k$, where each $b_i > 0$.

Theorem 9: There are $\binom{k-1}{s-1}$ *compositions* of $k > 0$ into s positive parts.

Theorem 10: The total number of compositions of $k > 0$ into *some* number of positive parts is

$$\sum_{s=1}^k \binom{k-1}{s-1} = 2^{k-1}$$

Parallel Summation Identity

Q: How many integer solutions are there to the *inequality* $b_1 + \dots + b_s \leq k$, where each $b_i \geq 0$?

Theorem 11: $\sum_{m=0}^k \binom{m+s-1}{m} = \binom{k+s}{k}$

Proof (hint): Introduce a “dummy” variable b_{s+1} to take up the *slack* between $b_1 + \dots + b_s$ and k .
Construct a bijection with the solutions to $b_1 + \dots + b_s + b_{s+1} = k$, where $b_i \geq 0$.

□

Set Partitions

Set Partitions

Definition 18: A *partition* of a set X is a set of non-empty subsets of X such that every element of X belongs to exactly one of these subsets.

Equivalently, a family of sets P is a partition of X iff:

1. The family P does not contain the empty set: $\emptyset \notin P$.
2. The union of P is X , that is, $\bigcup_{A \in P} A = X$. The sets in P are said to *cover* X .
3. The intersection of any two distinct sets in P is empty: $\forall A, B \in P. (A \neq B) \rightarrow (A \cap B = \emptyset)$.
The sets in P are said to be *pairwise disjoint* or *mutually exclusive*.

The sets in P are called *blocks*, *parts*, or *cells*, of the partition.

The block in P containing an element $x \in X$ is denoted by $[x]$.

Examples of Set Partitions

Example: The empty set $X = \emptyset$ has exactly one partition, $P = \emptyset$.

Example: Any singleton set $X = \{x\}$ has exactly one partition, $P = \{\{x\}\}$.

Example: For any non-empty proper subset $A \subset U$, the set A and its complement form a partition of U , namely $P = \{A, U - A\}$.

Example: The set $X = \{1, 2, 3\}$ has five partitions:

1. $\{\{1\}, \{2\}, \{3\}\}$ or $1 | 2 | 3$
2. $\{\{1\}, \{2, 3\}\}$ or $1 | 2 \ 3$
3. $\{\{1, 2\}, \{3\}\}$ or $1 \ 2 | 3$
4. $\{\{1, 3\}, \{2\}\}$ or $1 \ 3 | 2$
5. $\{\{1, 2, 3\}\}$ or $1 \ 2 \ 3$

Example: The following are *not* partitions of $\{1, 2, 3\}$:

- $\{\{\}, \{1, 3\}, \{2\}\}$, because it contains the empty set.
- $\{\{1, 2\}, \{2, 3\}\}$, because the element 2 is contained in more than one block.
- $\{\{1\}, \{3\}\}$, because no block contains the element 3.

Counting Set Partitions

Definition 19: The number of partitions of a set X (of size $n = |X|$) into k non-empty blocks (“unlabeled subsets”) is called a *Stirling number of the second kind* and denoted $S(n, k)$ or $\left\{ \begin{matrix} n \\ k \end{matrix} \right\}$.

Example: Let $X = \{1, 2, 3, 4\}$, $k = 2$. There are 7 possible partitions:

<table border="1"><tr><td>1</td><td>2</td></tr><tr><td>3</td><td>4</td></tr></table>	1	2	3	4	<table border="1"><tr><td>1</td><td>2</td></tr><tr><td>3</td><td>4</td></tr></table>	1	2	3	4	<table border="1"><tr><td>1</td><td>2</td></tr><tr><td>3</td><td>4</td></tr></table>	1	2	3	4	<table border="1"><tr><td>1</td><td>2</td></tr><tr><td>3</td><td>4</td></tr></table>	1	2	3	4	<table border="1"><tr><td>1</td><td>2</td></tr><tr><td>3</td><td>4</td></tr></table>	1	2	3	4	<table border="1"><tr><td>1</td><td>2</td></tr><tr><td>3</td><td>4</td></tr></table>	1	2	3	4	<table border="1"><tr><td>1</td><td>2</td></tr><tr><td>3</td><td>4</td></tr></table>	1	2	3	4
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Theorem 12: Let $\left\{ \begin{matrix} n \\ 0 \end{matrix} \right\} = 0$ for $n \geq 1$, $\left\{ \begin{matrix} 0 \\ k \end{matrix} \right\} = 0$ for $k \geq 1$, and $\left\{ \begin{matrix} 0 \\ 0 \end{matrix} \right\} = 1$. For $n, k \geq 1$, we have:

$$\left\{ \begin{matrix} n \\ k \end{matrix} \right\} = \left\{ \begin{matrix} n-1 \\ k-1 \end{matrix} \right\} + k \cdot \left\{ \begin{matrix} n-1 \\ k \end{matrix} \right\}$$

Proof (informal): TODO

□

Bell Numbers

Definition 20: The total number of partitions of a set X of size $n = |X|$ (into an arbitrary number of non-empty blocks) is called a *Bell number* and denoted B_n .

$$B_n = \sum_{k=0}^n \left\{ \begin{matrix} n \\ k \end{matrix} \right\}$$

Note: Consider the special case of $n = 0$. There is exactly *one* partition of \emptyset into non-empty parts:
 $\emptyset = \bigcup_{A \in \emptyset} A \in \emptyset$. Every $A \in \emptyset$ is non-empty, since no such A exists. Thus, we have $B_0 = S(0, 0) = 1$.

Bell Numbers [2]

Theorem 13: For $n \geq 1$, we have the recursive identity for Bell numbers:

$$B_n = \sum_{k=0}^{n-1} \binom{n-1}{k} B_k$$

Proof: Every partition of $[n]$ has one part that contains the number n . In addition to n , this part also contains k other numbers (for some $0 \leq k \leq n-1$). The remaining $n-1-k$ elements are partitioned arbitrarily. From this correspondence, we obtain the desired identity:

$$B_n = \sum_{k=0}^{n-1} \binom{n-1}{k} B_{n-1-k} = \sum_{k=0}^{n-1} \binom{n-1}{n-1-k} B_{n-1-k} = \sum_{k=0}^{n-1} \binom{n-1}{k} B_k$$

□

Integer Partitions

Integer Partitions

Definition 21: An *integer partition* of a positive integer $n \geq 1$ into k *positive* parts is a *solution* to the equation $n = a_1 + \dots + a_k$, where $a_1 \geq a_2 \geq \dots \geq a_k \geq 1$.

- The number of integer partitions of n into k positive non-decreasing parts is denoted $p_k(n)$ and defined recursively:

$$p_k(n) = \begin{cases} 0 & \text{if } k > n \\ 0 & \text{if } n \geq 1 \text{ and } k = 0 \\ 1 & \text{if } n = k = 0 \\ p_k(n - k) + p_{k-1}(n - 1) & \text{if } 1 \leq k \leq n \end{cases}$$

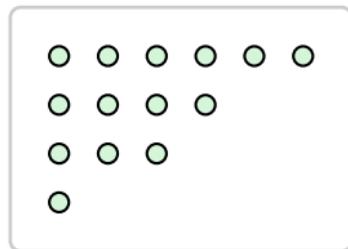
- The number of partitions of n (into an arbitrary number of parts) is the *partition function* $p(n)$:

$$p(n) = \sum_{k=0}^n p_k(n)$$

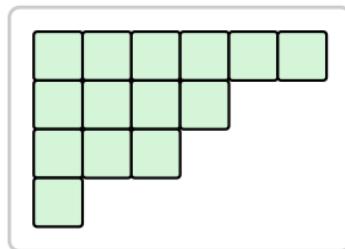
Ferrer Diagrams and Young Tableaux

Example: Consider an integer partition: $14 = 6 + 4 + 3 + 1$.

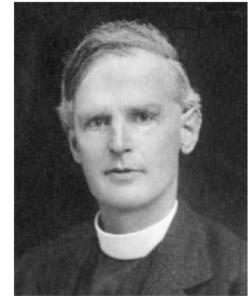
Ferrer Diagram



Young Tableaux



Norman Ferrer



Alfred Young

Inclusion–Exclusion

The Inclusion–Exclusion Principle

TODO: small example of PIE with 2 or 3 sets

Principle of Inclusion–Exclusion (PIE)

Theorem 14: Let X be a finite set and P_1, \dots, P_m properties.

- Define $X_i = \{x \in X \mid x \text{ has } P_i\}$, i.e. the set of all elements from X having a property P_i .
- Define for $S \subseteq [m]$ the set $N(S) = \{x \in X \mid \forall i \in S : x \text{ has } P_i\}$. Observe: $N(S) = \bigcap_{i \in S} X_i$.

The number of elements of X that satisfy *none* of the properties P_1, \dots, P_m is given by

$$|X \setminus (X_1 \cup \dots \cup X_m)| = \sum_{S \subseteq [m]} (-1)^{|S|} |N(S)| \quad (1)$$

Proof: Consider any $x \in X$. If $x \in X$ has none of the properties, then $x \in N(\emptyset)$ and $x \notin N(S)$ for any other $S \neq \emptyset$. Hence x contributes 1 to the sum (1).

If $x \in X$ has exactly $k \geq 1$ of the properties, call this set $T \in \binom{[m]}{k}$. Then $x \in N(S)$ iff $S \subseteq T$.

The contribution of x to the sum (1) is $\sum_{S \subseteq T} (-1)^{|S|} = \sum_{i=0}^k \binom{k}{i} (-1)^i = 0$, i.e. zero. □

Note: In the last step, we used that for any $y \in \mathbb{R}$ we have $(1 - y)^k = \sum_{i=0}^k \binom{k}{i} (-y)^i$ which implies (for $y = 1$) that $0 = \sum_{i=0}^k \binom{k}{i} (-1)^i$.

Very Useful Corollary of PIE

Corollary 14.1: 🐕

$$\left| \bigcup_{i \in [m]} X_i \right| = |X| - \sum_{S \subseteq [m]} (-1)^{|S|} |N(S)| = \sum_{\emptyset \neq S \subseteq [m]} (-1)^{|S|-1} |N(S)|$$

Applications of PIE

Let's state the principle of inclusion-exclusion using a rigid pattern:

1. *Define “bad” properties.*

Identify the things to count as the elements of some universe X except for the ones having *at least one* of the “bad” properties P_1, \dots, P_m . In other words, we want to count $X \setminus (X_1 \cup \dots \cup X_m)$.

2. *Count $N(S)$.*

For each $S \subseteq [m]$, determine $N(S)$, the number of elements of X having *all* bad properties P_i for $i \in S$.

3. *Apply PIE.*

Use Theorem 14 to obtain a closed formula for $|X \setminus (X_1 \cup \dots \cup X_m)|$.

Counting Surjections via PIE

Theorem 15: The number of surjections from $[k]$ to $[n]$ is given by

$$\left| \left\{ f : [k] \xrightarrow{\text{surj.}} [n] \right\} \right| = \sum_{i=0}^n (-1)^i \binom{n}{i} (n-i)^k$$

Proof: Let X be the set of all maps from $[k]$ to $[n]$.

1. *Define bad properties:* Define the “bad” property P_i for $i \in [n]$ as “ i is not in the image of f ”, i.e.

$$f : [k] \rightarrow [n] \text{ has property } P_i \leftrightarrow \forall j \in [k] : f(j) \neq i$$

The *surjective* functions are exactly those functions that *do not* have any of the “bad” properties.

2. *Count $N(S)$:* We claim $N(S) = (n - |S|)^k$ for any $S \subseteq [n]$. To see this, observe that f has all properties with indices from S if and only if $f(i) \notin S$ for all $i \in [k]$. In other words, f must be a function from $[k]$ to $[n] \setminus S$, and there are $(n - |S|)^k$ of those.

Counting Surjections via PIE [2]

3. *Apply PIE:* Using [Theorem 14](#), the number of surjections from $[k]$ to $[n]$ is

$$\begin{aligned}|X \setminus (X_1 \cup \dots \cup X_n)| &\stackrel{\text{PIE}}{=} \sum_{S \subseteq [n]} (-1)^{|S|} |N(S)| \\&= \sum_{S \subseteq [n]} (-1)^{|S|} (n - |S|)^k \\&= \sum_{i=0}^n (-1)^i \binom{n}{i} (n - i)^k\end{aligned}$$

In the last step, we used that $(-1)^{|S|}(n - |S|)^k$ only depends on the size of S , and there are $\binom{n}{i}$ sets $S \subseteq [n]$ of size i .

□

More Useful Corollaries

Corollary 15.1: Consider the case $n = k$. A function from $[n]$ to $[n]$ is a *surjection* iff it is a *bijection*. Since there are $n!$ bijections on $[n]$ (namely, all permutations), we have the following identity:

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

Corollary 15.2: A surjection from $[k]$ to $[n]$ can be seen as a partition of $[k]$ into n non-empty distinguishable (labeled) parts (the map assigns a part to each $i \in [k]$).

Since the partition of $[k]$ into n non-empty indistinguishable parts is denoted $s_n^{\text{II}}(k)$, and there are $n!$ ways to assign labels to n parts, we obtain that the number of surjections is equal to $n!s_n^{\text{II}}(k)$:

$$n!s_n^{\text{II}}(k) = \sum_{i=0}^n (-1)^i \binom{n}{i} (n-i)^k$$

Derangements

Theorem 16: The *derangements* D_n on n elements are permutations of $[n]$ without fixed points.

The number of derangements is given by

$$|D_n| = \sum_{i=0}^n (-1)^i \binom{n}{i} (n-i)!$$

Proof: Let X be the set of all permutations of $[n]$.

1. Define the “bad” property P_i to mean “ π has a fixpoint i ” ($i \in [n]$):

$$\pi \in X \text{ has property } P_i \leftrightarrow \pi(i) = i$$

2. We claim $N(S) = (n - |S|)!$ for any $S \subseteq [n]$.

Indeed, $\pi \in X$ has all properties with indices from S if and only if all $i \in S$ are fixed points of π . On the other elements, *i.e.* on $[n] \setminus S$, π may be an arbitrary bijection, so there are $(n - |S|)!$ choices for π .

Derangements [2]

3. Using Theorem 14, the number of derangements is given by

$$\begin{aligned}|X \setminus (X_1 \cup \dots \cup X_n)| &\stackrel{\text{PIE}}{=} \sum_{S \subseteq [n]} (-1)^{|S|} |N(S)| \\&= \sum_{S \subseteq [n]} (-1)^{|S|} (n - |S|)! \\&= \sum_{i=0}^n (-1)^i \binom{n}{i} (n - i)!\end{aligned}$$

In the last step, we used that $(-1)^{|S|}(n - |S|)!$ only depends on the size of S , and there are $\binom{n}{i}$ sets $S \subseteq [n]$ of size i .

□

Generating Functions

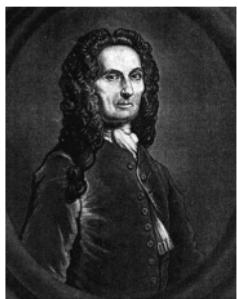
Generating Functions

A generating function is a device somewhat similar to a bag. Instead of carrying many little objects detachedly, which could be embarrassing, we put them all in a bag, and then we have only one object to carry, the bag.

— George Pólya, Mathematics and Plausible Reasoning [1]

A generating function is a clothesline on which we hang up a sequence of numbers for display.

— Herbert Wilf, generatingfunctionology [2]



Abraham
de Moivre



George Pólya



Herbert Wilf

Ordinary Generating Functions

Definition 22: An *ordinary generating function* (OGF) of a sequence a_n is a *power series*

$$G(a_n; x) = \sum_{n=0}^{\infty} a_n x^n$$

Example: The *sequence* $a_n = (a_0, a_1, a_2, \dots)$ is *generated* by the OGF $G(x) = a_0 + a_1 x + a_2 x^2 + \dots$

Example: $G(x) = 3 + 8x^2 + x^3 + \frac{1}{7}x^5 + 100x^6 + \dots$ *generates* the sequence $(3, 0, 8, 1, 0, \frac{1}{7}, 100, 0, \dots)$

Example: Consider a long division of 1 by $(1 - x)$, the result is an infinite power series

$$\frac{1}{1-x} = 1 + x^1 + x^2 + x^3 + \dots = \sum_{n=0}^{\infty} x^n$$

Note that all coefficients are 1. Thus, the generating function of $(1, 1, 1, \dots)$ is $G(x) = \sum_{n=0}^{\infty} x^n = \frac{1}{1-x}$.

The Core Generating Function

Another proof that $(1, 1, 1, \dots)$ is generated by $G(x) = 1 + x + x^2 + x^3 + \dots = \sum_{n=0}^{\infty} x^n = \frac{1}{1-x} = S$:

$$\begin{array}{rcl} S & = & 1 + x + x^2 + x^3 + \dots \\ x \cdot S & = & x + x^2 + x^3 + \dots \\ \hline S - x \cdot S & = & 1 \end{array}$$

Thus, $S = \frac{1}{1-x}$.

The generating function $G(x) = 1 + x + x^2 + \dots$ is also known as the *Maclaurin series* of $\frac{1}{1-x}$.

More Examples of Generating Functions

Formula	Power series	Sequence	Description
$\frac{1}{1-x}$	$\sum_{n=0}^{\infty} x^n = 1 + x + x^2 + x^3 + \dots$	(1, 1, 1, ...)	constant 1
$\frac{2}{1-x}$	$\sum_{n=0}^{\infty} 2x^n = 2 + 2x + 2x^2 + 2x^3 + \dots$	(2, 2, 2, ...)	constant 2
$\frac{x}{1-x}$	$\sum_{n=1}^{\infty} x^n = 0 + x + x^2 + x^3 + \dots$	(0, 1, 1, 1, ...)	right shift
$\frac{1}{1+x}$	$\sum_{n=0}^{\infty} (-1)^n x^n = 0 + 1 - x + x^2 - x^3 + \dots$	(1, -1, 1, ...)	sign-alternating 1's
$\frac{1}{1-3x}$	$\sum_{n=0}^{\infty} 3^n x^n = 1 + 3x + 9x^2 + 27x^3 + \dots$	(1, 3, 9, ...)	powers of 3

More Examples of Generating Functions [2]

Formula	Power series	Sequence	Description
$\frac{1}{1-x^2}$	$\sum_{n=0}^{\infty} x^{2n} = 1 + x^2 + x^4 + x^6 + \dots$	$(1, 0, 1, 0, \dots)$	regular gaps
$\frac{1}{(1-x)^2}$	$\sum_{n=0}^{\infty} (n+1)x^n = 1 + 2x + 3x^2 + 4x^3 + \dots$	$(1, 2, 3, 4, \dots)$	natural numbers
	$\begin{aligned}\frac{1-x^{n+1}}{1-x} &= \frac{1}{1-x} - \frac{x^{n+1}}{1-x} = \\ &\stackrel{\Delta}{=} (1, 1, 1, \dots) - (\underbrace{0, 0, \dots, 0}_{n+1 \text{ zeros}}, 1, 1, \dots) = \\ &= (\underbrace{1, 1, \dots, 1}_{n+1 \text{ ones}}, 0, 0, \dots) = \\ &\stackrel{\Delta}{=} 1 + x + x^2 + \dots + x^n\end{aligned}$		

Exercises

Example: Find GF for odd numbers: (1, 3, 5, ...).

Example: Find GF for (1, 3, 7, 15, 31, 63), which satisfies $a_n = 3a_{n-1} - 2a_{n-2}$ with $a_0 = 1, a_1 = 3$.

Solving Combinatorial Problems via Generating Functions

Example: Find the number of integer solutions to $y_1 + y_2 + y_3 = 12$ with $0 \leq y_i \leq 6$.

- Possible values for y_1 are $0 \leq y_1 \leq 6$.
 - There is a *single* way to select $y_1 = 0$. The same for other values among $1, \dots, 6$.
 - There are *no* ways to select any value of y_1 higher than 6.
 - The *number of ways to select y_1 to be equal to n* forms a sequence $(1, 1, 1, 1, 1, 1, 1, 0, \dots)$.
 - Write this sequence as a polynomial $x^0 + x^1 + \dots + x^6$.
 - Do the same for y_2 and y_3 (*in isolation!*).
- Since all combinations of y_1 , y_2 and y_3 are valid non-conflicting solutions, we can multiply those polynomials and obtain the *generating function* $G(x) = (1 + x + x^2 + \dots + x^6)^3$.
 - For each n , the coefficient of x^n in $G(x)$ is the number of integer solutions to $x_1 + x_2 + x_3 = n$.
 - In particular, we are interested in the coefficient of x^{12} in $G(x)$, denoted $[x^{12}]G(x)$.
 - Use ~~pen and paper~~ Wolfram Alpha to expand $G(x)$:

$$G(x) = x^{18} + 3x^{17} + 6x^{16} + \dots + \underline{28x^{12}} + \dots + 6x^2 + 3x + 1$$

- The *answer* is $[x^{12}]G(x) = 28$ solutions.

Slightly More Complex Combinatorial Problem

Example: Suppose we have marbles of three different colors (, , ), and we want to *count* the number of ways to select 20 marbles, such that:

- There are an even number of : $1 + x^2 + x^4 + \dots + x^{20}$.
- There are at least 12 : $x^{12} + x^{13} + \dots + x^{20}$.
- There are at most 5 : $1 + x + x^2 + x^3 + x^4 + x^5$.

Multiply polynomials and find $[x^{20}]G(x)$:

$$\begin{aligned}[x^{20}](1 + x^2 + x^4 + \dots + x^{20})(x^{12} + x^{13} + \dots + x^{20})(1 + x + x^2 + x^3 + x^4 + x^5) &= \\ &= [x^{20}]\left(x^{45} + 2x^{44} + \dots + \underline{21x^{20}} + \dots + 2x^{13} + x^{12}\right) \\ &= 21\end{aligned}$$

Using Power Series in Combinatorial Problems

Example: Find the number of integer solutions to $a_1 + a_2 + a_3 = 12$ with $a_1 \geq 2$, $3 \leq a_2 \leq 6$, $0 \leq a_3 \leq 9$.

- Compose the generating function:

$$G(x) = (x^2 + x^3 + \dots) \cdot (x^3 + x^4 + x^5 + x^6) \cdot (1 + x + x^2 + \dots + x^9)$$

- Substitute the power series with the corresponding simple forms:

$$G(x) = \left(x^2 \cdot \frac{1}{1-x} \right) \cdot \left(x^3 \cdot \frac{1-x^4}{1-x} \right) \cdot \left(\frac{1-x^{10}}{1-x} \right)$$

- Expand the series:

$$\begin{aligned} G(x) = & x^5 + 3x^6 + 6x^7 + 10x^8 + 14x^9 + 18x^{10} + \underline{22x^{11}} + 30x^{13} + \\ & 34x^{14} + 37x^{15} + 39x^{16} + 40x^{17} + \dots + 40x^n + \dots \end{aligned}$$

- Sequence: $(g_n) = (0, 0, 0, 0, 0, 1, 3, 6, 10, 14, 18, 22, 26, 30, 34, 37, 39, \overline{40}, \dots)$
- Answer for $n = 12$ is $[x^{12}]G(x) = 26$.

Operations on Generating Functions

Let $F(x) = \sum_{n=0}^{\infty} a_n x^n$ and $G(x) = \sum_{n=0}^{\infty} b_n x^n$ be ordinary generating functions.

Operation	Result
Differentiate $F(x)$ term-wise	$F'(x) = \sum_{n=0}^{\infty} (n+1) a_{n+1} x^n$
Multiply $F(x)$ by a scalar $\lambda \in \mathbb{R}$ term-wise	$\lambda F(x) = \sum_{n=0}^{\infty} \lambda a_n x^n$
Add $F(x)$ and $G(x)$ term-wise	$F(x) + G(x) = \sum_{n=0}^{\infty} (a_n + b_n) x^n$
Multiply $F(x)$ and $G(x)$ term-wise (<i>Cauchy product</i> , or <i>convolution</i>)	$F(x) \cdot G(x) = \sum_{n=0}^{\infty} \left(\sum_{k=0}^n a_k b_{n-k} \right) x^n$

Well-Formed Parenthesis Expressions

Example: Find the number of *well-formed parenthesis expressions* with n pairs of parenthesis.

For example, “((())())” is a well-formed parenthesis expression with 4 pairs of parenthesis.

Formally, a permutation of the multiset $\{n \cdot "(", n \cdot ")"\}$ is *well-formed* if reading it from left to right and counting “+1” for every opening parenthesis “(“ and “−1” for every closing parenthesis “)” never yields a negative number at any time.

Every well-formed expression with $n \geq 1$ pairs of parenthesis starts with “(“ and there is a unique matching “)” such that the sequence in between and the sequence after are well-formed. For example:

$$(())() \quad ((())()) \quad ()((())()$$

In other words, a well-formed expression with n pairs of parenthesis is obtained by putting a well-formed expression with k pairs in between “(“ and “)” and then appending a well-formed expression with $n - k - 1$ pairs of parenthesis. This gives the equation:

$$a_n = \sum_{k=0}^{n-1} a_k a_{n-k-1}$$

Well-Formed Parenthesis Expressions [2]

Let $F(x)$ be a generating function for a_n , then we know:

$$\begin{aligned} F(x) &= \sum_{n=0}^{\infty} a_n x^n = 1 + \sum_{n=1}^{\infty} \left(\sum_{k=0}^{n-1} a_k a_{n-k-1} \right) x^n = 1 + \sum_{n=0}^{\infty} \left(\sum_{k=0}^n a_k a_{n-k} \right) x^{n+1} \\ &= 1 + x \cdot \sum_{n=0}^{\infty} \left(\sum_{k=0}^n a_k a_{n-k} \right) x^n = 1 + x \cdot F(x)^2 \end{aligned}$$

Solving the equation $xF^2 - F + 1 = 0$ for F gives:

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

We are only interested in the root with the *minus* sign, since $\lim_{x \rightarrow 0} F(x) = a_0 = 1$:

$$\lim_{x \rightarrow 0} F(x) = \lim_{x \rightarrow 0} \frac{1 - \sqrt{1 - 4x}}{2x} = \lim_{x \rightarrow 0} \frac{\frac{2}{\sqrt{1-4x}}}{2} = 1$$

Newton's Binomial Theorem

Let's revisit the binomial theorem:

$$(1 + x)^n = \sum_{k=0}^n \binom{n}{k} x^k = \sum_{k=0}^{\infty} \binom{n}{k} x^k \quad \forall n \in \mathbb{N}$$

where $\binom{n}{k} = 0$ for $k > n$.

Note: This shows that $(1 + x)^n$ is the generating function for the series $(a_k)_{k \in \mathbb{N}}$ with $a_k = \binom{n}{k}$.

We can extend this result from natural numbers $n \in \mathbb{N}$ to any *real* number $n \in \mathbb{R}$.

Binomial Coefficients for Real Numbers

Definition 23: Let $p(n, k) = n \cdot (n - 1) \cdot \dots \cdot (n - k + 1)$, also called the *falling factorial* n^k .

Extend the definition of binomial coefficients for real numbers $n, k \in \mathbb{R}$:

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

Note: This definition aligns with the definition of binomial coefficients for natural numbers:

$$\binom{n}{k} = \frac{n!}{k! \cdot (n - k)!} = \frac{n \cdot (n - 1) \cdot \dots \cdot (n - k + 1)}{k!}$$

Example: Consider the number “ $-7 / 2$ choose 5”:

$$\binom{-7 / 2}{5} = \frac{-\frac{7}{2} \cdot -\frac{9}{2} \cdot -\frac{11}{2} \cdot -\frac{13}{2} \cdot -\frac{15}{2}}{5!} = -\frac{9009}{256}$$

Note: $p(n, 0) = 1$ and for $k \geq 1$, we have $p(n, k) = (n - k + 1) \cdot p(n, k - 1) = n \cdot p(n - 1, k - 1)$. (\star)

Extended Newton's Binomial Theorem

Theorem 17: For all non-zero $n \in \mathbb{R}$, we have:

$$(1 + x)^n = \sum_{k=0}^{\infty} \binom{n}{k} x^k$$

Example: Let $n = 1 / 2$, then we have an identity for $\sqrt{1+x}$:

$$\sqrt{1+x} = \sum_{k=0}^{\infty} \binom{1/2}{k} x^k$$

To actually *use* this fact, we need some *lemma*...

Lemma 18: For any integer $n \geq 1$, we have:

$$\binom{1/2}{n} = (-1)^{n+1} \cdot \binom{2n-2}{n-1} \cdot \frac{1}{2^{2n-1}} \cdot \frac{1}{n}$$

Extended Newton's Binomial Theorem [2]

Proof: By induction on n .

Base: $n = 1$. $\binom{1/2}{1} = \frac{1/2}{1!} = \frac{1}{2} = 1 \cdot 1 \cdot \frac{1}{2} \cdot 1 = \underbrace{(-1)^2}_1 \cdot \underbrace{\binom{2-2}{1-1}}_1 \cdot \underbrace{\frac{1}{2^{2-1}}}_{\frac{1}{2}} \cdot \underbrace{\frac{1}{1}}_1$

Induction step: n to $n + 1$ for $n > 1$. We use the recursion (\star) $p(n, k) = n \cdot p(n - 1, k - 1)$:

$$\begin{aligned}\binom{1/2}{n+1} &= \frac{p(1/2, n+1)}{(n+1)!} = \frac{(1/2 - (n+1)+1) \cdot p(1/2, n)}{(n+1) \cdot n!} = -\frac{n-1/2}{n+1} \binom{1/2}{n} \quad \square \\ &\stackrel{\text{IH}}{=} -\frac{n-1/2}{n+1} (-1)^{n+1} \cdot \binom{2n-2}{n-1} \cdot \frac{1}{2^{2n-1}} \cdot \frac{1}{n} \\ &= \frac{2n}{2n} \cdot \frac{2n-1}{2n} \cdot (-1)^{n+2} \cdot \binom{2n-2}{n-1} \cdot \frac{1}{2^{2n-1}} \cdot \frac{1}{n+1} \\ &= (-1)^{n+2} \cdot \underbrace{\frac{(2n-2)! \cdot (2n-1) \cdot (2n)}{(n-1)! \cdot (n-1) \cdot n \cdot n}}_{\binom{2n}{n}} \cdot \frac{1}{2^{2n+1}} \cdot \frac{1}{n+1}\end{aligned}$$

Catalan Numbers

Proposition 19: Now we can expand $\sqrt{1+n}$ into the following series:

$$\sqrt{1+n} = \sum_{n=0}^{\infty} \binom{1/2}{n} x^n = 1 + \sum_{n=1}^{\infty} -2 \cdot \binom{2n-2}{n-1} \cdot (-1)^n \cdot \frac{1}{2^{2n}} \cdot \frac{1}{n} \cdot x^n$$

Example: Going back to the example with the number of well-formed parenthesis expressions, we get:

$$\begin{aligned} F(x) &= \frac{1 - \sqrt{1 - 4x}}{2x} = \frac{1}{2x} \sum_{n=1}^{\infty} 2 \cdot \binom{2n-2}{n-1} \cdot (-1)^n \cdot \frac{1}{2^{2n}} \cdot \frac{1}{n} \cdot (-4x)^n \\ &= \frac{1}{x} \sum_{n=1}^{\infty} \binom{2n-2}{n-1} \frac{1}{n} x^n = \sum_{n=0}^{\infty} \binom{2n}{n} \frac{1}{n+1} x^n \end{aligned}$$

The numbers $C_n := \binom{2n}{n} \frac{1}{n+1}$ are called *Catalan numbers*.

Recurrence Relations

Recurrence Relations

Example:

- *Recurrent relation* defining a sequence (a_n) :

$$a_n = \begin{cases} a_0 = \text{const if } n = 0 \\ a_{n-1} + d \quad \text{if } n > 0 \end{cases}$$

- *Solving* it results in a non-recursive *closed* formula:

$$a_n = a_0 + n \cdot d$$

- *Checking* it confirms that the formula is correct:

$$a_n = \underbrace{a_{n-1}}_{a_{n-1}} + d = \underbrace{a_0 + (n-1)d}_{a_{n-1}} + d = a_0 + n \cdot d \quad \blacksquare$$

Linear Homogeneous Recurrence Relations

Definition 24: A *linear homogeneous* recurrence relation of degree k with constant coefficients is a recurrence relation of the form

$$a_n = c_1 a_{n-1} + c_2 a_{n-2} + \dots + c_k a_{n-k},$$

where c_1, c_2, \dots, c_k are constants (real or complex numbers), and $c_k \neq 0$.

Examples:

- $b_n = 2.71b_{n-1}$ is a linear homogeneous recurrence relation of degree 1.
- $F_n = F_{n-1} + F_{n-2}$ is a linear homogeneous recurrence relation of degree 2.
- $g_n = 2g_{n-5}$ is a linear homogeneous recurrence relation of degree 5.
- The recurrence relation $a_n = a_{n-1} + a_{n-2}^2$ is *not linear*.
- The recurrence relation $H_n = 2H_{n-1} + 1$ is *not homogeneous*.
- The recurrence relation $B_n = nB_{n-1}$ does *not* have *constant* coefficients.

Characteristic Equations

Hereinafter, $(*)$ denotes a linear homogeneous recurrence relation $a_n = c_1 a_{n-1} + c_2 a_{n-2} + \dots + c_k a_{n-k}$.

Theorem 20: $a_n = r^n$ is a solution to $(*)$ if and only if $r^n = c_1 r^{n-1} + c_2 r^{n-2} + \dots + c_k r^{n-k}$.

Definition 25: A *characteristic equation* for $(*)$ is the algebraic equation in r defined as:

$$r^k - c_1 r^{k-1} - c_2 r^{k-2} - \dots - c_k = 0$$

The sequence (a_n) with $a_n = r^n$ (with $r_n \neq 0$) is a solution if and only if r is a solution of the characteristic equation. Such solutions are called *characteristic roots* of $(*)$.

Distinct Roots Case

Theorem 21: Let c_1 and c_2 be real numbers. Suppose that $r^2 - c_1r - c_2 = 0$ has two *distinct* roots r_1 and r_2 . Then the sequence (a_n) is a solution of the recurrence relation $a_n = c_1a_{n-1} + c_2a_{n-2}$ if and only if $a_n = \alpha_1r_1^n + \alpha_2r_2^n$ for $n = 0, 1, 2, \dots$, where α_1 and α_2 are constants.

Proof (sketch): Since r_1 and r_2 are roots, then $r_1^2 = c_1r_1 + c_2$ and $r_2^2 = c_1r_2 + c_2$. Next, we can see:

$$\begin{aligned}c_1a_{n-1} + c_2a_{n-2} &= c_1(\alpha_1r_1^{n-1} + \alpha_2r_2^{n-1}) + c_2(\alpha_1r_1^{n-2} + \alpha_2r_2^{n-2}) \\&= \alpha_1r_1^{n-2}(c_1r_1 + c_2) + \alpha_2r_2^{n-2}(c_1r_2 + c_2) \\&= \alpha_1r_1^{n-2}r_1^2 + \alpha_2r_2^{n-2}r_2^2 \\&= \alpha_1r_1^n + \alpha_2r_2^n \\&= a_n\end{aligned}$$

To show that every solution (a_n) of the recurrence relation $a_n = c_1a_{n-1} + c_2a_{n-2}$ has $a_n = \alpha_1r_1^n + \alpha_2r_2^n$ for some constants α_1 and α_2 , suppose that the initial condition are $a_0 = C_0$ and $a_1 = C_1$, and show that there exist constants α_1 and α_2 such that $a_n = \alpha_1r_1^n + \alpha_2r_2^n$ satisfies the same initial conditions. \square

Solving Recurrence Relations using Characteristic Equations

Example: Solve $a_n = a_{n-1} + 2a_{n-2}$ with $a_0 = 2$ and $a_1 = 7$.

- The *characteristic* equation is $r^2 - r - 2 = 0$.
- It has two *distinct* roots $r_1 = 2$ and $r_2 = -1$.
- The sequence (a_n) is a solution iff $a_n = \alpha_1 r_1^n + \alpha_2 r_2^n$ for $n = 0, 1, 2, \dots$ and some constants α_1 and α_2 .

$$\begin{cases} a_0 = 2 = \alpha_1 + \alpha_2 \\ a_1 = 7 = \alpha_1 \cdot 2 + \alpha_2 \cdot (-1) \end{cases}$$

- Solving these two equations gives $\alpha_1 = 3$ and $\alpha_2 = -1$.
- Hence, the *solution* to the recurrence equation with given initial conditions is the sequence (a_n) with

$$a_n = 3 \cdot 2^n - (-1)^n$$

Fibonacci Numbers

Example: Find the closed formula for Fibonacci numbers.

- The recurrence relation is $F_n = F_{n-1} + F_{n-2}$.
- The characteristic equation is $r^2 - r - 1 = 0$.
- The roots are $r_1 = (1 + \sqrt{5})/2$ and $r_2 = (1 - \sqrt{5})/2$.
- Therefore, the solution is $F_n = \alpha_1\left(\frac{1+\sqrt{5}}{2}\right)^n + \alpha_2\left(\frac{1-\sqrt{5}}{2}\right)^n$ for some constants α_1 and α_2 .
- Using the initial conditions $F_0 = 0$ and $F_1 = 1$, we get

$$\begin{cases} F_0 = \alpha_1 + \alpha_2 = 0 \\ F_1 = \alpha_1 \cdot \left(\frac{1+\sqrt{5}}{2}\right) + \alpha_2 \cdot \left(\frac{1-\sqrt{5}}{2}\right) = 1 \end{cases}$$

- Solving these two equations gives $\alpha_1 = 1/\sqrt{5}$ and $\alpha_2 = -1/\sqrt{5}$.
- Hence, the *closed formula* (also known as Binet's formula) for Fibonacci numbers is

$$F_n = \underbrace{\frac{1}{\sqrt{5}} \left(\frac{1 + \sqrt{5}}{2} \right)^n}_{\varphi} - \underbrace{\frac{1}{\sqrt{5}} \left(\frac{1 - \sqrt{5}}{2} \right)^n}_{\psi} = \frac{\varphi^n - \psi^n}{\sqrt{5}}$$

Single (Repeated) Root Case

Theorem 22: Let c_1 and c_2 be real numbers. Suppose that $r^2 - c_1r - c_2 = 0$ has a *single (repeated)* root r_0 . A sequence (a_n) is a solution of the recurrence relation $a_n = c_1a_{n-1} + c_2a_{n-2}$ if and only if $a_n = (\alpha_1 + \alpha_2n)r_0^n$ for $n = 0, 1, 2, \dots$, where α_1 and α_2 are constants.

Example: Solve $a_n = 6a_{n-1} - 9a_{n-2}$ with $a_0 = 1$ and $a_1 = 6$.

The characteristic equation is $r^2 - 6r + 9 = 0$ with a single (repeated) root $r_0 = 3$. Hence, the solutions is of the form $a_n = (\alpha_1 + \alpha_2n)3^n$.

$$\begin{cases} a_0 = 1 = \alpha_1 \\ a_1 = 6 = (\alpha_1 + \alpha_2) \cdot 3 \end{cases} \implies \begin{cases} \alpha_1 = 1 \\ \alpha_2 = 1 \end{cases}$$

Thus, the *solution* is $a_n = (1 + n)3^n$.

General Case

Theorem 23: Let c_1, \dots, c_k be real numbers. Suppose that the recurrence $a_n = c_1 a_{n-1} + \dots + c_k a_{n-k}$ has t distinct characteristic roots r_1, \dots, r_t with multiplicities m_1, \dots, m_t , respectively, so that $m_i \geq 1$ for $i = 1, \dots, t$ and $m_1 + \dots + m_t = k$.

Then the general form of the recurrence relation is given by

$$a_n = \sum_{i=1}^t \left(r_i^n \cdot \sum_{j=0}^{m_i-1} \alpha_{i,j} x^j \right)$$

where $\alpha_{i,j}$ are constants for $1 \leq i \leq t$ and $0 \leq j \leq m_i - 1$.

Example: Find generic solution for $a_n = 7a_{n-1} - 16a_{n-2} + 12a_{n-3}$.

The characteristic equation $r^3 - 7r^2 + 16r - 12 = 0$ has $t = 2$ distinct roots: $r_1 = 2$ repeated $m_1 = 2$ times, and $r_2 = 3$ with multiplicity $m_2 = 1$. Hence, the solution is of the form

$$a_n = (\alpha_{1,0} + \alpha_{1,1} n) 2^n + \alpha_{2,0} 3^n$$

Complex Case

Example: Solve the recurrence $a_n = 6a_{n-1} - 16a_{n-2} + 25a_{n-3} - 20a_{n-4} + 8a_{n-5}$ with the initial conditions $a_0 = 2, a_1 = 2, a_2 = 0, a_3 = -4, a_4 = -8$.

Characteristic equation is $r^5 - 6r^4 + 16r^3 - 25r^2 + 20r - 8 = 0$.

Characteristic roots are: $r_1 = (1 - i)$, repeated twice, $r_2 = (1 + i)$, also repeated twice, and $r_3 = 2$.

General solution has the form:

$$a_n = (\alpha_{1,0} + \alpha_{1,1}n)(1 - i)^n + (\alpha_{2,0} + \alpha_{2,1}n)(1 + i)^n + \alpha_{3,0} 2^n$$

To find the constants, we can use the initial conditions:

$$\begin{cases} a_0 = 2 = \alpha_{1,0} + \alpha_{1,1} & + \alpha_{2,0} + \alpha_{2,1} & + \alpha_{3,0} \\ a_1 = 2 = (\alpha_{1,0} + \alpha_{1,1})(1 - i) & + (\alpha_{2,0} + \alpha_{2,1})(1 + i) & + 2\alpha_{3,0} \\ a_2 = 0 = (\alpha_{1,0} + 2\alpha_{1,1})(1 - i)^2 & + (\alpha_{2,0} + 2\alpha_{2,1})(1 + i)^2 & + 4\alpha_{3,0} \\ a_3 = -4 = (\alpha_{1,0} + 3\alpha_{1,1})(1 - i)^3 & + (\alpha_{2,0} + 3\alpha_{2,1})(1 + i)^3 & + 8\alpha_{3,0} \\ a_4 = -8 = (\alpha_{1,0} + 4\alpha_{1,1})(1 - i)^4 & + (\alpha_{2,0} + 4\alpha_{2,1})(1 + i)^4 & + 16\alpha_{3,0} \end{cases} \Rightarrow \begin{cases} \alpha_{1,0} = 1 \\ \alpha_{1,1} = 0 \\ \alpha_{2,0} = 1 \\ \alpha_{2,1} = 0 \\ \alpha_{3,0} = 0 \end{cases}$$

Linear Non-Homogeneous Recurrence Relations

$$a_n = c_1 a_{n-1} + c_2 a_{n-2} + \dots + c_k a_{n-k} + F(n)$$

Example: $a_n = 3a_{n-1} + 2n$ is non-homogeneous.

Definition 26: An *associated homogeneous recurrence relation* is the relation without the term $F(n)$.

Solving Non-Homogeneous Recurrence Relations

Theorem 24: If $(a_n^{(p)})$ is a *particular* solution of the non-homogeneous linear recurrence relation $a_n = c_1 a_{n-1} + c_2 a_{n-2} + \dots + c_k a_{n-k} + F(n)$, then *every solution* is of the form $(a_n^{(p)} + a_n^{(h)})$, where $(a_n^{(h)})$ is a solution of the associated homogeneous recurrence relation.

Example: Find all solutions of the recurrence relation $a_n = 3a_{n-1} + 2n$. What is the solution with $a_1 = 3$?

- First, solve the associated homogeneous recurrence relation $a_n = 3a_{n-1}$.
- It has a general solution $a_n^{(h)} = \alpha 3^n$, where α is a constant.
- To find a particular solution, observe that $F(n) = 2n$ is a polynomial in n of degree 1, so a reasonable trial solution is a linear function in n , for example, $p_n = cn + d$, where c and d are constants.
- Thus, the equation $a_n = 3a_{n-1} + 2n$ becomes $cn + d = 3(c(n-1) + d) + 2n$.
- Simplify and reorder: $(2 + 2c)n + (2d - 3c) = 0$.

$$\begin{cases} 2 + 2c = 0 \\ 2d - 3c = 0 \end{cases} \Rightarrow \begin{cases} c = -1 \\ d = -3/2 \end{cases}$$

- Thus, $a_n^{(p)} = -n - 3/2$ is a *particular* solution.

Solving Non-Homogeneous Recurrence Relations [2]

- By Theorem 24, all solutions are of the form

$$a_n = a_n^{(p)} + a_n^{(h)} = -n - 3/2 + \alpha 3^n,$$

where α is a constant.

- To find the solution with $a_1 = 3$, let $n = 1$ in the formula: $3 = -1 - 3/2 + 3\alpha$, thus $\alpha = 11/6$.
- The *solution* is $a_n = -n - 3/2 + (11/6)3^n$.

Annihilators

Operators

Definition 27: *Operators* are higher-order functions that transform functions into other functions.

For example, differential and integral operators $\frac{d}{dx}$ and $\int dx$ are core operators in calculus.

In combinatorics, we are interested in the following three operators:

- *Sum*: $(f + g)(n) := f(n) + g(n)$
- *Scale*: $(\alpha \cdot f)(n) := \alpha \cdot f(n)$
- *Shift*: $(E f)(n) := f(n + 1)$

Examples:

- Scale and Shift operators are *linear*: $E(f - 3(g - h)) = E f + (-3) E g + 3 E h$
- Operators are *composable*: $(E - 2)f := E f + (-2)f$
- $E^2 f = E(E f)$
- $E^k f(n) = f(n + k)$
- $(E - 2)^2 = (E - 2)(E - 2)$
- $(E - 1)(E - 2) = E^2 - 3 E + 2$

Applying Operators

Examples: Below are the results of applying different operators to $f(n) = 2^n$:

$$2f(n) = 2 \cdot 2^n = 2^{n+1}$$

$$3f(n) = 3 \cdot 2^n$$

$$\mathbf{E} f(n) = 2^{n+1}$$

$$\mathbf{E}^2 f(n) = 2^{n+2}$$

$$(\mathbf{E} - 2)f(n) = \mathbf{E} f(n) - 2f(n) = 2^{n+1} - 2^{n+1} = 0$$

$$(\mathbf{E}^2 - 1)f(n) = \mathbf{E}^2 f(n) - f(n) = 2^{n+2} - 2^n = 3 \cdot 2^n$$

Compound Operators

The compound operators can be seen as polynomials in “variable” E .

Example: The compound operators $E^2 - 3E + 2$ and $(E-1)(E-2)$ are equivalent:

$$\text{Let } g(n) := (E-2)f(n) = f(n+1) - 2f(n)$$

$$\begin{aligned}\text{Then } (E-1)(E-2)f(n) &= (E-1)g(n) \\ &= g(n+1) - g(n) \\ &= [f(n+2) - 2f(n-1)] - [f(n+1) - 2f(n)] \\ &= f(n+2) - 3f(n+1) + 2f(n) \\ &= (E^2 - 3E + 2)f(n) \quad \checkmark\end{aligned}$$

Operators Summary

Operator	Definition
addition	$(f + g)(n) := f(n) + g(n)$
subtraction	$(f - g)(n) := f(n) - g(n)$
multiplication	$(\alpha \cdot f)(n) := \alpha \cdot f(n)$
shift	$\mathbf{E} f(n) := f(n + 1)$
k-fold shift	$\mathbf{E}^k f(n) := f(n + k)$
composition	$(\mathbf{X} + \mathbf{Y})f := \mathbf{X} f + \mathbf{Y} f$ $(\mathbf{X} - \mathbf{Y})f := \mathbf{X} f - \mathbf{Y} f$ $\mathbf{X} \mathbf{Y} f := \mathbf{X}(\mathbf{Y} f) = \mathbf{Y}(\mathbf{X} f)$
distribution	$\mathbf{X}(f + g) = \mathbf{X} f + \mathbf{X} g$

Annihilators

Definition 28: An *annihilator* of a function f is any non-trivial operator that transforms f into zero.

TODO: examples!

Annihilators Summary

Operator	Functions annihilated
$\mathbf{E} - 1$	α
$\mathbf{E} - a$	αa^n
$(\mathbf{E} - a)(\mathbf{E} - b)$	$\alpha a^n + \beta b^n$ [if $a \neq b$]
$(\mathbf{E} - a_0)(\mathbf{E} - a_1) \dots (\mathbf{E} - a_k)$	$\sum_{i=0}^k \alpha_i a_i^n$ [if a_i are distinct]
$(\mathbf{E} - 1)^2$	$\alpha n + \beta$
$(\mathbf{E} - a)^2$	$(\alpha n + \beta)a^n$
$(\mathbf{E} - a)^2(\mathbf{E} - b)$	$(\alpha n + \beta)a^n + \gamma b^n$ [if $a \neq b$]
$(\mathbf{E} - a)^d$	$\left(\sum_{i=0}^{d-1} \alpha_i n^i\right)a^n$

Properties of Annihilators

Theorem 25: If \mathbf{X} annihilates f , then \mathbf{X} also annihilates αf for any constant α .

Theorem 26: If \mathbf{X} annihilates both f and g , then \mathbf{X} also annihilates $f \pm g$.

Theorem 27: If \mathbf{X} annihilates f , then \mathbf{X} also annihilates $\mathbf{E} f$.

Theorem 28: If \mathbf{X} annihilates f and \mathbf{Y} annihilates g , then $\mathbf{X} \mathbf{Y}$ annihilates $f \pm g$.

Annihilating Recurrences

1. Write the recurrence in the *operator form*.
2. Find the *annihilator* for the recurrence.
3. *Factor* the annihilator, if necessary.
4. Find the *generic solution* from the annihilator.
5. Solve for coefficients using the *initial conditions*.

Example: $r(n) = 5r(n - 1)$ with $r(0) = 3$.

1. $r(n + 1) - 5r(n) = 0$
 $(E - 5)r(n) = 0$
2. $(E - 5)$ annihilates $r(n)$.
3. $(E - 5)$ is already factored.
4. $r(n) = \alpha 5^n$ is a generic solution.
5. $r(0) = \alpha = 3 \implies \alpha = 3$

Thus, $r(n) = 3 \cdot 5^n$.

Annihilating Recurrences [2]

Example: $T(n) = 2T(n - 1) + 1$ with $T(0) = 0$

1. $T(n + 1) - 2T(n) = 1$

$$(\mathbf{E} - 2)T(n) = 1$$

2. $(\mathbf{E} - 2)$ does *not* annihilate $T(n)$: the residue is 1.

$(\mathbf{E} - 1)$ annihilates the residue 1.

Thus, $(\mathbf{E} - 1)(\mathbf{E} - 2)$ annihilates $T(n)$.

3. $(\mathbf{E} - 1)(\mathbf{E} - 2)$ is already factored.

4. $T(n) = \alpha 2^n + \beta$ is a generic solution.

5. Find the coefficients α, β using $T(0) = 0$ and $T(1) = 2T(0) + 1 = 1$:

$$\begin{cases} T(0) = 0 = \alpha \cdot 2^0 + \beta \\ T(1) = 1 = \alpha \cdot 2^1 + \beta \end{cases} \implies \begin{cases} \alpha = 1 \\ \beta = -1 \end{cases}$$

Thus, $T(n) = 2^n - 1$.

Annihilating Recurrences [3]

Example: $T(n) = T(n - 1) + 2T(n - 2) + 2^n - n^2$

1. Operator form:

$$(\mathbf{E}^2 - \mathbf{E} - 2)T(n) = \mathbf{E}^2(2^n - n^2)$$

2. Annihilator:

$$(\mathbf{E}^2 - \mathbf{E} - 2)(\mathbf{E} - 2)(\mathbf{E} - 1)^3$$

3. Factorization:

$$(\mathbf{E} + 1)(\mathbf{E} - 2)^2(\mathbf{E} - 1)^3$$

4. Generic solution:

$$T(n) = \alpha(-1)^n + (\beta n + \gamma)2^n + \delta n^2 + \varepsilon n + \zeta$$

5. There are no initial conditions. We can only provide an asymptotic bound.

Thus, $T(n) \in \Theta(n2^n)$

Asymptotic Analysis

Asymptotics 101

Definition 29 (Big-O notation): The notation $f \in O(g)$ means that the function $f(n)$ is *asymptotically bounded from above* by the function $g(n)$, up to a constant factor.

$$f(n) \in O(g(n)) \Leftrightarrow \exists c > 0. \exists n_0. \forall n > n_0 : |f(n)| \leq c \cdot g(n)$$

Definition 30 (Small-o notation): The notation $f \in o(g)$ means that the function $f(n)$ is *asymptotically dominated* by $g(n)$, up to a constant factor.

$$f(n) \in o(g(n)) \Leftrightarrow \forall c > 0. \exists n_0. \forall n > n_0 : |f(n)| \leq c \cdot g(n)$$

Note: The difference is only in the $\exists c$ and $\forall c$ quantifier.

Note: Flip \leq to \geq in the above definitions to obtain the dual notations: $f \in \Omega(g)$ and $f \in \omega(g)$.

Definition 31 (Theta notation): $f \in \Theta(g)$ iff $f \in O(g)$ and $g \in O(f)$.

Limits

Notation	Name	Description	Limit definition
$f \in o(g)$	Small Oh	f is dominated by g	$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 0$
$f \in O(g)$	Big Oh	f is bounded above by g	$\limsup_{n \rightarrow \infty} \frac{ f(n) }{g(n)} < \infty$
$f \sim g$	Equivalence	f is asymptotically equal to g	$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 1$
$f \in \Omega(g)$	Big Omega	f is bounded below by g	$\liminf_{n \rightarrow \infty} \frac{f(n)}{g(n)} > 0$
$f \in \omega(g)$	Small Omega	f dominates g	$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = \infty$

Asymptotic Equivalence

Definition 32: The notation $f \sim g$ means that functions $f(n)$ and $g(n)$ are *asymptotically equivalent*.

$$f \sim g \leftrightarrow \forall \varepsilon > 0. \exists n_0. \forall n > n_0 : \left| \frac{f(n)}{g(n)} - 1 \right| \leq \varepsilon \leftrightarrow \lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 1$$

Note: $f \sim g$ and $g \sim f$ are equivalent, since \sim is an equivalence relation.

Note: $f \sim g$ and $f \in \Theta(g)$ are *different* notions!

Some Properties of Asymptotics

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

$$f \in O(g) \Leftrightarrow g \in \Omega(f)$$

$$f \in o(g) \Leftrightarrow g \in \omega(f)$$

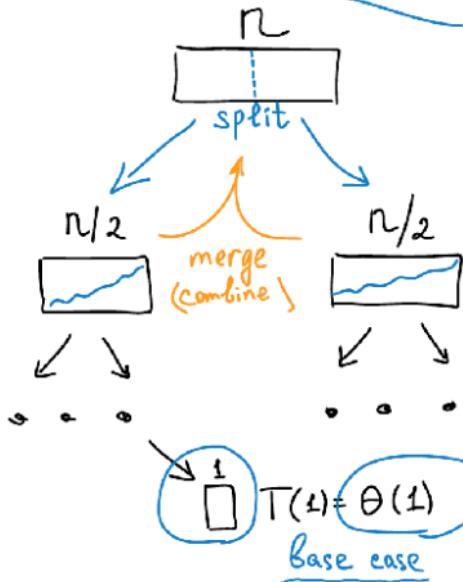
$$f \in o(g) \rightarrow f \in O(g)$$

$$f \in \omega(g) \rightarrow f \in \Omega(g)$$

$$f \sim g \rightarrow f \in \Theta(g)$$

Divide-and-Conquer Algorithms Analysis

Divide-and-Conquer



$$T(n) = 2 T(n/2) + \Theta(n)$$

recursive work split/merge work

$$\left\{ \begin{array}{l} \sum = 2 \cdot 2 \cdot T(n/4) = n \\ \text{merge} \end{array} \right.$$
$$\left\{ \begin{array}{l} \sum \approx 2^{i+1} T(n/2^i) = n \end{array} \right.$$

$\Theta(n) \cdot \Theta(\log n) = \Theta(n \log n)$

work on each level of recursion tree
height of recursion tree

Divide-and-Conquer Recurrence

$$T(n) = a \cdot T\left(\frac{n}{b}\right) + f(n)$$

- $T(n)$ is the *cost* of the recursive algorithm
- a is the number of *parts (sub-problems)*
- n / b is the *size* of each part
- $T\left(\frac{n}{b}\right)$ is the cost of each *sub-problem*
- $f(n)$ is the cost of *splitting* and *merging* the solutions of the subproblems

Hereinafter, $c_{\text{crit}} = \log_b a$ is a *critical constant*.

Master Theorem

The master theorem [3] applies to divide-and-conquer recurrences of the form

$$T(n) = a \cdot T\left(\frac{n}{b}\right) + f(n)$$

Case	Description	Condition	Bound
Case I	“merge” \ll “recursion”	$f(n) \in O(n^c)$ where $c < c_{\text{crit}}$	$T(n) \in \Theta(n^{c_{\text{crit}}})$
Case II	“merge” \approx “recursion”	$f(n) \in \Theta(n^{c_{\text{crit}}} \log^k n)$ where $k \geq 0$	$T(n) \in \Theta(n^{c_{\text{crit}}} \log^{k+1} n)$
Case III	“merge” \gg “recursion”	$f(n) \in \Omega(n^c)$ where $c > c_{\text{crit}}$	$T(n) \in \Theta(f(n))$

Note: Case III also requires the *regularity condition* to hold: $af(n / b) \leq kf(n)$ for some constant $k < 1$ and all sufficiently large n .

Note: There is an *extended* Case II, with three sub-cases (IIa, IIb, IIc) for other values of k . See [wiki](#).

Examples of Master Theorem Application

Examples: Determine the case of Master Theorem and the bound of $T(n)$ for the following recurrences.

1. $T(n) = 3T(n / 9) + \sqrt{n}$

2. $T(n) = 2T(n / 4) + n^{0.51}$

3. $T(n) = 5T(n / 25) + n^{0.49}$

4. $T(n) = T(\lfloor \frac{n}{2} \rfloor) + T(\lceil \frac{n}{2} \rceil)$

5. $T(n) = 3T(n / 9) + \frac{\sqrt{n}}{\log n}$

6. $T(n) = 6T(n / 36) + \frac{\sqrt{n}}{\log^2 n}$

7. $T(n) = 4T(n / 16) + \sqrt{\frac{n}{\log n}}$

Akra–Bazzi Method

The Akra–Bazzi method [4] is a *generalization* of the master theorem to recurrences of the form

$$T(n) = f(n) + \sum_{i=1}^k a_i T\left(b_i n + \underbrace{h_i(n)}_{*}\right)$$

- k is a constant
- $a_i > 0$
- $0 < b_i < 1$
- $h_i(n) \in O\left(\frac{n}{\log^2 n}\right)$ is a *small perturbation*

Bound of $T(n)$ by Akra–Bazzi method:

$$T(n) \in \Theta\left(n^p \cdot \left(1 + \int_1^n \frac{f(x)}{x^{p+1}} dx\right)\right)$$

where p is the solution for the equation $\sum_{i=1}^k a_i b_i^p = 1$

Example of Akra–Bazzi Method Application

Example: Suppose the runtime of an algorithm is expressed by the following recurrence relation:

$$T(n) = \begin{cases} 1 & \text{for } 0 \leq n \leq 3 \\ n^2 + \frac{7}{4}T(\lfloor \frac{1}{2}n \rfloor) + T(\lceil \frac{3}{4}n \rceil) & \text{for } n > 3 \end{cases}$$

- Note that the Master Theorem *is not* applicable here, since there are *two* different recursive terms.
- Let's apply the Akra–Bazzi method. First, solve the equation $\frac{7}{4}\left(\frac{1}{2}\right)^p + \left(\frac{3}{4}\right)^p = 1$. This gives us $p = 2$.
- Next, use the formula from AB-method to obtain the bound:

$$\begin{aligned} T(x) &\in \Theta\left(x^p \left(1 + \int_1^x \frac{f(u)}{u^{p+1}} du\right)\right) = \\ &= \Theta\left(x^2 \left(1 + \int_1^x \frac{u^2}{u^3} du\right)\right) = \\ &= \Theta(x^2(1 + \ln x)) = \\ &= \Theta(x^2 \log x) \end{aligned}$$

Advanced Topics

Gamma Function

Definition 33: *Gamma function* $\Gamma(x)$ is the most common *extension* of the factorial function to real and complex numbers. It is defined for all complex numbers $z \in \mathbb{C}$ (except non-positive integers) as

$$\Gamma(z) = \int_0^{\infty} t^{z-1} e^{-t} dt$$

For positive integers $z = n$, it is defined as

$$\Gamma(n) = (n - 1)!$$

Motivation: The factorial is defined for positive integers as $n! = 1 \cdot 2 \cdot \dots \cdot n = (n - 1)! \cdot n$.

We want to *extend* this definition to *all real numbers* and capture its *recursive* nature.

Overall, we are looking for a *smooth* function $\Gamma(x)$ such that:

- $\Gamma(n + 1) = n!$ for all $n \in \mathbb{N}$, matching the factorial.
- $\Gamma(x + 1) = x \cdot \Gamma(x)$, satisfying a *recursive* property.
- $\Gamma(x)$ is defined for all *real* numbers $x > 0$.

Definition of a Gamma Function

The main definition of a gamma function is known as *Euler integral of the second kind*:

$$\Gamma(z) = \int_0^{\infty} t^{z-1} e^{-t} dt$$

Gauss proposed a function $\Gamma(x)$ defined by the *limit*

$$\Gamma(x) := \lim_{n \rightarrow \infty} \frac{n! \cdot n^x}{x \cdot (x+1) \cdot \dots \cdot (x+n)} = \lim_{n \rightarrow \infty} \frac{n! \cdot n^x}{\prod_{k=0}^n (x+k)} \quad \text{for } x > 0$$

Integral Definition

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt$$

Let's check that the integral definition is indeed a suitable definition of a gamma function.

$$\begin{aligned}\Gamma(z+1) &= \int_0^\infty t^z e^{-t} dt \\ &= [-t^z e^{-t}]_0^\infty + \int_0^\infty z t^{z-1} e^{-t} dt \\ &= \lim_{t \rightarrow \infty} (-t^z e^{-t}) - (-0^z e^{-0}) + z \int_0^\infty t^{z-1} e^{-t} dt\end{aligned}$$

Note that $-t^z e^{-t} \rightarrow 0$ as $t \rightarrow \infty$, so:

$$\Gamma(z+1) = z \int_0^\infty t^{z-1} e^{-t} dt = z \cdot \Gamma(z)$$

Limit Definition

$$\Gamma(x) = \lim_{n \rightarrow \infty} \frac{n! \cdot n^x}{\prod_{k=0}^n (x+k)}$$

Let's check that the limit definition is indeed a suitable definition of a gamma function.

Step 1. Write $\Gamma(x+1)$.

$$\Gamma(x+1) = \lim_{n \rightarrow \infty} \frac{n! \cdot n^{x+1}}{\prod_{k=0}^n (x+1+k)} = \lim_{n \rightarrow \infty} \frac{n! \cdot n^{x+1}}{\prod_{k=1}^{n+1} (x+k)}$$

Step 2. Multiply both numerator and denominator by x and rearrange:

$$= \lim_{n \rightarrow \infty} \frac{n! \cdot n^{x+1}}{(x+1) \cdot \dots \cdot (x+n+1)} = \lim_{n \rightarrow \infty} \frac{n! \cdot n^x}{x \cdot (x+1) \cdot \dots \cdot (x+n)} \cdot \frac{n}{x+n+1} \cdot x$$

Step 3. Take the limit. As $n \rightarrow \infty$, the ratio $\frac{n}{x+n+1}$ approaches 1.

$$\Gamma(x+1) = x \cdot \Gamma(x)$$

Equivalence of Definitions

Let's prove the equivalence of two definitions: integral and limit.

We claim:

$$\int_0^n t^{x-1} \left(1 - \frac{t}{n}\right)^n dt \stackrel{?}{=} \lim_{n \rightarrow \infty} \frac{n! \cdot n^x}{x \cdot (x+1) \cdot \dots \cdot (x+n)}$$

Note that as $n \rightarrow \infty$, the integrand $\left(1 - \frac{t}{n}\right)^n$ approaches e^{-t} , so this integral approximates $\Gamma(x)$.

Substitute $u = \frac{t}{n}$:

$$\int_0^n t^{x-1} \left(1 - \frac{t}{n}\right)^n dt = n^x \int_0^1 u^{x-1} (1-u)^n du = n^x \cdot B(x, n+1)$$

where $B(x, n+1)$ is the Beta function:

$$B(x, y) = \int_0^1 t^{x-1} (1-t)^{y-1} dt = \frac{\Gamma(x) \cdot \Gamma(y)}{\Gamma(x+y)}$$

Equivalence of Definitions [2]

Then:

$$I_n = n^x \cdot B(x, n+1) = n^x \cdot \frac{\Gamma(x) \cdot \Gamma(n+1)}{\Gamma(x+n+1)} = \frac{n! \cdot n^x}{x \cdot (x+1) \cdot \dots \cdot (x+n)}$$

Take the limit on both sides. Since $\lim_{n \rightarrow \infty} I_n = \Gamma(x)$, we have:

$$\Gamma(x) = \lim_{n \rightarrow \infty} \frac{n! \cdot n^x}{x \cdot (x+1) \cdot \dots \cdot (x+n)}$$

Using the Gamma Function

$$n! = \Gamma(n + 1)$$

$$\binom{r}{k} = \frac{\Gamma(r + 1)}{\Gamma(k + 1) \cdot \Gamma(r - k + 1)}$$

$$\Gamma(n + 1) \approx \sqrt{2\pi n} \left(\frac{n}{e} \right)^n$$

$$\text{B}(x, y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x + y)}$$

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