
MA 861 : COMBINATORICS I

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§0. Notation and Prerequisites

Given $n \in \mathbb{N}$, $[n]$ denotes the set $\{1, \dots, n\}$ and $[n]_0$ denotes the set $[n] \cup \{0\}$.

$S(n, k)$, a Stirling number of the second kind, is the number of partitions of $[n]$ into exactly k parts. $s(n, k)$, a Stirling number of the first kind, is the number of permutations of $[n]$ with exactly k cycles.

Given a graph G and edge $e \in G$, $G - e$ is the graph obtained by deleting e (it has the same vertex set), and $G \setminus e$ is the graph obtained by “contracting” e , that is, merging the two vertices of e and having a vertex adjacent to the new vertex if they are adjacent to either of the earlier vertices.

§1. Introduction

Exercise 1.1. Recall that the number of k -subsets of $[n]$ is $\binom{n}{k}$. Given a k -subset $S = \{x_1, \dots, x_k\}$ of $[n]$, we write $S_{<} = \{x_1, \dots, x_k\}_{<}$ to denote that $x_1 < x_2 < \dots < x_k$. Determine the number of k -subsets $\{x_1, \dots, x_k\}_{<}$ of $[n]$ such that $x_i \equiv i \pmod{2}$.

For example, for $n = 6$ and $k = 3$, we have the subsets $\{1, 4, 5\}, \{1, 2, 3\}, \{1, 2, 5\}, \{3, 4, 5\}$.

Broadly, there are three types of “answers”: a formula, a recurrence, and a generating function. A great example of the second and third is the following.

$p(n)$, the number of number partitions of n , is given by the generating function

$$\sum_{n \geq 0} p(n)x^n = \prod_{i \geq 1} \frac{1}{1 - x^i}.$$

Using this, a recursion may be obtained as well. We do *not* plug in values for x in the above. We merely look at the coefficient of x^n in it. We want the coefficient to be a finite sum for all n . If it is an infinite sum, convergence issues may arise.

1.1. Counting in \mathfrak{S}_n

Recall that \mathfrak{S}_n is generated by transpositions. A transposition (i, j) is a permutation σ defined by

$$\sigma(k) = \begin{cases} j, & k = i, \\ i, & k = j, \\ k, & \text{otherwise.} \end{cases}$$

In fact, \mathfrak{S}_n is generated by the set of just “adjacent transpositions” $S_i = (i, i + 1)$ for $1 \leq i < n$. We have

$$\begin{aligned} S_i^2 &= \text{Id} \\ S_i S_{i+1} S_i &= S_{i+1} S_i S_{i+1} \\ S_i S_j &= S_j S_i \text{ if } |i - j| > 2. \end{aligned}$$

Definition 1.1. Given a permutation $\pi \in \mathfrak{S}_n$, define the *length* $\ell(\pi)$ of π to be the smallest k such that there exist adjacent transpositions $\sigma_1, \dots, \sigma_k$ such that $\pi = \sigma_1 \cdots \sigma_k$.

Proposition 1.1. Consider the *inversion number* $\text{inv}(\pi)$ of a permutation, defined by

$$\text{inv}(\pi) = |\{1 \leq i \leq j \leq n : \pi_i > \pi_j\}|.$$

Then, $\ell(\pi) = \text{inv}(\pi)$.

Definition 1.2. The *sign* of a permutation π is defined by $\text{sign}(\pi) = (-1)^{\text{inv}(\pi)}$. Equivalently,

$$\text{sign}(\pi) = \frac{\prod_{1 \leq i < j \leq n} (x_{\pi_i} - x_{\pi_j})}{\prod_{1 \leq i < j \leq n} (x_i - x_j)}.$$

It is straightforward to see that for all $\pi \in \mathfrak{S}_n$, $0 \leq \text{inv}(\pi) \leq \binom{n}{2}$.

Proposition 1.2. Consider $\text{inv}_n(q) = \sum_{\pi \in \mathfrak{S}_n} q^{\text{inv}(\pi)}$. Then,

$$\text{inv}_n(q) = \prod_{1 \leq m \leq n} [m]_q,$$

where

$$[m]_q = \begin{cases} 1 + q + \cdots + q^{m-1}, & m \geq 1, \\ 0, & m = 0. \end{cases}$$

This quantity $[m]_q$ is called the q -analogue of m , and similarly, the q -analogue of $n!$ is $\prod_{i=1}^n [i]_q$ (this is slightly vague). Note in particular that $n! = \text{inv}_n(1)$.

Proof. We prove this by induction. It is easily verified for $n = 2$.

Take $\sigma \in \mathfrak{S}_{n-1}$. There are n “gaps” where n can be “placed” in σ to get a permutation in \mathfrak{S}_n . If we place it in the i th position from the end (for $0 \leq i \leq n-1$), the inversion number of the newly obtained permutation is i more than the inversion number of σ .

As a result,

$$\text{inv}_n(q) = \text{inv}_{n-1}(q) + q \text{inv}_{n-1}(q) + q^2 \text{inv}_{n-1}(q) + \cdots + q^{n-1} \text{inv}_{n-1}(q) = [n]_q \text{inv}_{n-1}(q),$$

where the $q^i \text{inv}_{n-1}(q)$ term corresponds to the case where n is placed in the i th position from the end. The required follows by the inductive hypothesis. ■

Definition 1.3 (Descent). For $\pi \in \mathfrak{S}_n$, define the *descents* $\text{DES}(\pi) = \{i \in [n-1] : \pi_i > \pi_{i+1}\}$, $\text{des}(\pi) = |\text{DES}(\pi)|$, and $\text{maj}(\pi) = \sum_{i \in \text{DES}(\pi)} i$.

Some books define the number of descents as $\text{des}(\pi) + 1$ instead.

There are central limit theorems for many of these parameters, which we shall not study.

A permutation π has $\text{des}(\pi) + 1$ many “increasing runs”.

For example, for the permutation $\pi = (1 \mapsto 5, 2 \mapsto 1, 3 \mapsto 2, 4 \mapsto 6, 5 \mapsto 4, 6 \mapsto 3) \in \mathfrak{S}_6$, $\text{DES}(\pi) = \{1, 4, 5\}$, $\text{des}(\pi) = 3$, and $\text{maj}(\pi) = 10$.

Proposition 1.3. The distribution of $\text{maj}(\pi)$ over \mathfrak{S}_n is the same as that of $\text{inv}(\pi)$. Equivalently,

$$\text{maj}_n(q) = \sum_{\pi \in \mathfrak{S}_n} q^{\text{maj}(\pi)} = \prod_{m=1}^n [m]_q = \text{inv}_n(q).$$

This result took nearly 50 years to prove!

Proof. The strategy is similar to that of Proposition 1.2. Let $\pi \in \mathfrak{S}_{n-1}$. As before, there are n positions to insert n .

- Label the positions of descents of σ and the last position from right to left as $0, 1, \dots, \text{des}(\pi)$.
- Label the remaining positions from left to right as $\text{des}(\pi) + 1, \dots, n-1$.

We claim that inserting n at a position increases maj by the labelled amount.

If inserted anywhere, all the descent positions starting from there increase by 1. This explains why the increase is equal to the labelled quantity for positions that are descents, since no new descents are introduced. In the case where we insert it in a position of non-descent, we further introduce a new descent at the position of insertion of n , which explains why the increase is equal to the labelled quantity for positions that are not descents.

The remainder of the proof is identical to that of Proposition 1.2, since the increases are in bijection with $[n-1]_0$. ■

Definition 1.4. A parameter $f : \mathfrak{S}_n \rightarrow \mathbb{R}$ of permutations such that

$$\sum_{\pi \in \mathfrak{S}_n} q^{f(\pi)} = \prod_{1 \leq m \leq n} [m]_q$$

is said to be *Mahonian*.

As we saw in ?? 1.2?? 1.3, both inv and maj are Mahonian.

1.2. Counting spanning trees

Problem. Count the number of spanning trees in an arbitrary (finite) graph G .

This was solved by Kirchhoff using the Matrix Tree Theorem.

Theorem 1.4 (Matrix Tree Theorem). Consider the *Laplacian* $L = D - A$ of a graph G , where A is its adjacency matrix and D is a diagonal matrix with the diagonal entries being the degrees of the vertices. The determinant of any $(n - 1) \times (n - 1)$ submatrix of L obtained by omitting any arbitrary row and column is equal to the number of spanning trees of G .

In particular, when $G = K_n$, we end up getting the following.

Theorem 1.5 (Cayley's Theorem). The number of spanning trees in K_n is n^{n-2} .

One proof by Prüfer gives an explicit bijection between spanning trees and sequences (v_1, \dots, v_{n-2}) of vertices in G . Another proof is of course using the matrix tree theorem, which reduces it to a simple determinant calculation. Joyal gave another bijection between elements of the form (T, u, v) where T is a spanning tree and u, v are vertices in G , and functions from $[n] \rightarrow [n]$.

The proof we give uses exponential generating functions. Recall the following result, which we give without proof. Interested readers may consult Corollary 5.1.6 of [SF99] for further details.

Theorem 1.6 (Exponential Formula). Let $\{f_n\}$ be a sequence with exponential generating function

$$F(x) = \sum_{n \geq 1} f_n \frac{x^n}{n!}.$$

Define the sequence h_n by

$$h_n = \sum_{\substack{\pi \in \text{SetPartn}([n]) \\ \pi = \{S_1, \dots, S_k\}}} f_{|S_1|} f_{|S_2|} \cdots f_{|S_k|}$$

and $h_0 = 1$, and let

$$H(x) = \sum_{n \geq 0} h_n \frac{x^n}{n!}.$$

Then,

$$H(x) = \exp(F(x))$$

Note that the summation of F is for $n \geq 1$, because we may assume that $f_0 = 0$ since f_0 does not appear in the expression of any h_n .

Definition 1.5 (Compositional inverse). Generating functions F and G are said to be *compositional inverses* (of each other) if $F(G(x)) = G(F(x)) = x$.

Let

$$F(x) = \sum_{n \geq 0} f_n x^n \text{ and } G(x) = \sum_{n \geq 0} g_n x^n$$

be compositional inverses of each other. It is reasonably straightforward to show that $f_0 = g_0 = 0$ and $f_1, g_1 \neq 0$. The first condition implies that the coefficient of any x^n in $F \circ G$ (or $G \circ F$) is finite.

Theorem 1.7 (Lagrange Inversion Theorem). Let

$$F(x) = \sum_{n \geq 0} f_n x^n \text{ and } G(x) = \sum_{n \geq 0} g_n x^n$$

be compositional inverses of each other. Then, ng_n is the coefficient of $1/x$ in $(1/F(x))^n$.

Equivalently, ng_n is the coefficient of x^{n-1} in $(x/F(x))^n$.

Proof. We have

$$x = G(F(x)) = \sum_{i \geq 0} g_i F(x)^i.$$

Differentiating,

$$1 = \sum_{i \geq 0} g_i i F(x)^{i-1} F'(x).$$

As a result,

$$\left(\frac{1}{F(x)} \right)^n = \sum_{i \geq 0} g_i i F(x)^{i-1-n} F'(x).$$

Whenever $i \neq n$, the coefficient of $1/x$ in $F(x)^{i-1-n} F'(x) = (F(x)^{i-n}/(i-n))'$ is zero. Indeed, recall that the coefficient of $1/x$ in the derivative of any power series with possibly negative exponents is zero.

As a result, the coefficient of $1/x$ in $(1/F(x))^n$ is equal to the coefficient of $1/x$ in $g_n n F'(x)/F(x)$. We have

$$\frac{F'(x)}{F(x)} = \frac{f_1 + 2f_2x + \cdots}{f_1x + f_2x^2 + \cdots}.$$

The coefficient of $1/x$ in this is $f_1/f_1 = 1$, and the desideratum follows. ■

At long last, let us return to **Cayley's Theorem**.

Proof of Cayley's Theorem. Instead of looking at the number T_n of spanning trees, we shall look at RT_n , the number of *rooted* spanning trees. Clearly, $RT_n = nT_n$.

Define RF_n to be the number of rooted forests on $[n]$ and let

$$RF(x) = \sum_{n \geq 0} RF_n \frac{x^n}{n!}$$

$$RT(x) = \sum_{n \geq 0} RT_n \frac{x^n}{n!}.$$

Using Theorem 1.6, it is not too difficult to see that

$$\text{RF}(x) = \exp(\text{RT}(x)). \quad (1.1)$$

Claim (Polya). $\text{RT}_{n+1} = (n+1)\text{RF}_n$.

Indeed, any rooted tree on K_{n+1} may be obtained from a rooted forest F on K_n by adding a new vertex v , adding the edge between each root in F and v to the spanning tree, removing the “root status” from all vertices except v . v can be labelled in $n+1$ ways, so we are done.

As a result,

$$\text{RF}(x) = \sum_{n \geq 0} \frac{\text{RT}_{n+1}}{n+1} \cdot \frac{x^n}{n!} = \frac{1}{x} \text{RT}(x). \quad (1.2)$$

Combining Equations (1.1) and (1.2),

$$\text{RT}(x) = x \exp(\text{RT}(x)).$$

That is, RT is the compositional inverse of $x \mapsto xe^{-x}$. Now, we use the **Lagrange Inversion Theorem** to get that $n\text{RT}_n/n!$ is equal to the coefficient of x^{n-1} in $(x/xe^{-x})^n = e^{nx}$, which is $n^{n-1}/(n-1)!$. Therefore, $T_n = \text{RT}_n/n = n^{n-2}$ and we are done. ■

1.3. Chebyshev polynomials

We would like a polynomial $T_n(x)$ such that $T_n(\cos \theta) = \cos(n\theta)$. Why does such a polynomial even exist? Recall that

$$(\cos \theta + i \sin \theta)^n = \cos n\theta + i \sin n\theta.$$

Since the real part of the left only has even powers of \sin , we can convert it to a polynomial of $\cos \theta$ s alone. For example,

$$\begin{aligned} T_0(x) &= 1, \\ T_1(x) &= x, \\ T_2(x) &= 2x^2 - 1. \end{aligned}$$

Proposition 1.8.

$$T_n(x) = \begin{cases} 1, & n = 0, \\ x, & n = 1, \\ 2xT_{n-1}(x) - T_{n-2}(x), & n \geq 2. \end{cases}$$

We give the proof of the above in the solution to Proposition 1.9.

Proposition 1.9. $T_0(x) = 1, T_1(x) = x$, and for $n \geq 2$,

$$T_n(x) = 2xT_{n-1}(x) - T_{n-2}(x).$$

Proof. Let $\cos \theta = x$. We have

$$\begin{aligned} T_n(x) &= \cos n\theta = \cos(n-1)\theta \cos \theta - \sin(n-1)\theta \sin \theta \\ &= xT_{n-1}(x) - (\sin(n-2)\theta \cos \theta + \cos(n-2)\theta \sin \theta) \sin \theta \\ &= xT_{n-1}(x) - T_{n-2}(x)(1-x^2) - x(\sin \theta \sin(n-2)\theta) \\ &= xT_{n-1}(x) + x^2T_{n-2}(x) - T_{n-2}(x) - x(\cos \theta \cos(n-2)\theta - \cos(n-1)\theta) \\ &= 2xT_{n-1}(x) - T_{n-2}(x). \end{aligned} \quad \blacksquare$$

Definition 1.6 (Chebyshev polynomials). The n th Chebyshev polynomial of the first kind T_n is defined as above. The n th Chebyshev polynomial of the second kind U_n is defined by

$$U_n(x) = \begin{cases} 1, & n = 0, \\ 2x, & n = 1, \\ 2xU_{n-1}(x) - U_{n-2}(x), & n \geq 2. \end{cases}$$

Consider the number of tilings of a $1 \times n$ board B_n using squares (1×1 pieces) and dimers (1×2 pieces). It is not too difficult to show that this corresponds to the Fibonacci numbers.

Now, instead consider a *weighted* version of this problem, where we give squares a weight of $2x$ and dimers a weight of -1 . The weight $\text{wt}(T)$ of a given tiling T is equal to the product of the weights of the pieces used. Then, the Chebyshev polynomial U_n is just the sum of the weights of all tilings of B_n !

$$U_n(x) = \sum_{\text{tilings } T \text{ of } B_n} \text{wt}(T).$$

Similar to this, we can get a combinatorial model for T_n as well, with the only difference being that a square piece has weight x if it is at the leftmost $(1, 1)$ position.

Given a tiling T , let $S(T)$ and $D(T)$ be the number of squares and dimers in the tiling respectively. In general, define

$$F_n(s, t) = \sum_{\text{tilings } T \text{ of } B_n} s^{S(T)} t^{D(T)}.$$

Then,

$$\begin{aligned} F_0(s, t) &= 1, \\ F_1(s, t) &= s, \\ F_n(s, t) &= sF_{n-1}(s, t) + tF_{n-2}(s, t). \end{aligned}$$

1.4. More on q -analogues

Recall the definition of $[n]_q! = \prod_{i=1}^n [i]_q$. Inspired by this, define

$$\binom{n}{k}_q = \frac{[n]_q!}{[k]_q! [n-k]_q!}.$$

This is clearly a rational function of q . It turns out that this is a polynomial in q ! For example,

$$\binom{5}{2}_q = \frac{[5]_q [4]_q}{[2]_q [1]_q} = 1 + q + 2q^2 + 2q^3 + 2q^4 + q^5 + q^6.$$

Recall that

$$\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}.$$

Exercise 1.2. Show that

$$\binom{n}{k}_q = q^k \binom{n-1}{k}_q + \binom{n-1}{k-1}_q = \binom{n-1}{k}_q + q^{n-k} \binom{n-1}{k-1}_q.$$

These are called the q -Pascal's recurrences.

Corollary 1.10. $\binom{n}{k}_q$ is a polynomial in q with non-negative coefficients.

It turns out that the coefficients of the polynomial are unimodal and symmetric! We do not prove this, the reader can see [1] for more details.

A natural question to ask then is: what do the coefficients of this polynomial count?

Let $\binom{n}{k}_q = f_{n,k}(q) = \sum_{r \geq 0} a_{n,k}^{(r)} q^r$. Can we have

$$\binom{n}{k}_q = \sum_{T \in \binom{[n]}{k}} q^{\text{parameter}(T)}?$$

$a_{n,k}^{(r)}$ then just counts the number of T with the given parameter value.

Recall that $\binom{n}{k}$ is the number of paths from $(0, 0)$ to $(n - k, k)$ if only upwards and rightwards movements on the integer lattice \mathbb{Z}^2 are allowed. Let P be such a path.

Consider the portion of the box above P . This can be viewed as the Ferrer diagram of some number partition $\lambda(P)$. $\lambda(P)$ has at most k parts, and no part is of size more than $n - k$. In fact, *all* such partitions correspond to some path! What number is $\lambda(P)$ a number partition of? Denote this number as $|\lambda(P)|$. Let $S_{n,k}$ be the set of all paths of the mentioned form.

Theorem 1.11.

$$\sum_{P \in S_{n,k}} q^{|\lambda(P)|} = \binom{n}{k}_q.$$

Perhaps surprisingly, the proof of the above is near-straightforward using the q -Pascal recurrence – merely consider two cases depending on whether the first step of the path is right or upwards.

1.5. Derivative polynomials

We begin this section by recalling the following rather interesting result.

Define the *Bell polynomial* $B_{n,k}$ by

$$B_{n,k}(x_1, x_2, \dots, x_{n-k+1}) = \sum \frac{n!}{j_1!(1!)^{j_1} j_2!(2!)^{j_2} \dots j_{n-k+1}!((n-k+1)!)^{j_{n-k+1}}} \cdot x_1^{j_1} x_2^{j_2} \dots x_{n-k+1}^{j_{n-k+1}},$$

where the summation is taken over all indices j_1, \dots, j_{n-k+1} of non-negative integers such that

$$\begin{aligned} k &= j_1 + j_2 + \dots + j_{n-k+1} \text{ and} \\ n &= j_1 + 2j_2 + 3j_3 + \dots + (n-k+1)j_{n-k+1}. \end{aligned}$$

This has a natural correspondence to the Stirling numbers of the second kind, with j_i representing the number of partitions of size i . In particular, the sum of coefficients of $B_{n,k}$ is $S_{n,k}$.

Proposition 1.12 (Faà di Bruno's Formula, [dB55]).

$$D^n f(g(x)) = \sum f^{(k)}(g(x)) \cdot B_{n,k}(g'(x), g''(x), \dots, g^{(n-k+1)}(x)).$$

To illustrate this better, let us look at the first few derivatives explicitly. Dropping the (x) on the right to make the notation more succinct, we have

$$\begin{aligned} Df(g(x)) &= f'(g)g' \\ D^2f(g(x)) &= f''(g)(g')^2 + f'(g)g'' \\ D^3f(g(x)) &= f'''(g)(g')^3 + 3f''(g)g'g'' + f'(g)g''' \end{aligned}$$

Consider the partitions of $\{1, 2, 3\}$, given by $1|2|3$, $12|3$, $13|2$, $23|1$, and 123 . The number of partitions of $[n]$ with n_i parts of size i for each i neatly corresponds to the coefficient of $\prod_i (g^{(i)})^{n_i}!$

Let $y = f(x)$. If $Dy = p(f(x))$ for some polynomial p , then $D^n y$ is a polynomial of f as well.

Suppose that $D^n y = p_n(y)$ for some sequence of polynomials (p_n) .

Exercise 1.3. Show that

$$\begin{aligned} p_0(y) &= y \\ p_n(y) &= \begin{cases} y & n = 0 \\ p_{n-1}(y) \cdot p_1(y) & n \geq 1. \end{cases} \end{aligned}$$

For the remainder of this section, set $y = \tan x$ and $z = \sec x$. Then, $Dy = 1 + y^2 = z^2$ and $Dz = yz$. It is not difficult to see that

$$\begin{aligned} D^2y &= 2yz^2 \\ D^3y &= 4y^2z^2 + 2z^4 \\ D^4y &= 8y^3z^2 + 16yz^4 \end{aligned}$$

Exercise 1.4. With y, z defined as above, show that

1. $D^n y$ is a homogeneous polynomial in y, z of degree $(n + 1)$.
2. $D^n y$ has only terms with even exponents of z .

Corollary 1.13. We can write $D^n y = \sum_{k=0}^{\lfloor (n-1)/2 \rfloor} W_{n,k} z^{2k+2} y^{n-2k-1}$.

Exercise 1.5. Prove or disprove that

$$\sum W_{n,k} = n!.$$

Again, we ask the question: is there some parameter on $\pi \in \mathfrak{S}_n$ such that

$$W_n(x) = \sum_{k=0}^{\lfloor (n-1)/2 \rfloor} W_{n,k} x^k = \sum_{\pi \in \mathfrak{S}_n} x^{\text{parameter}(\pi)}?$$

Definition 1.7 (Peak). Given a permutation $\pi \in \mathfrak{S}_n$, we say that $i \in [n] \setminus \{1, n\}$ is a *peak* of π if $\pi_i > \pi_{i-1}$ and $\pi_i > \pi_{i+1}$. Denote the set of peaks of π by $\text{Peak}(\pi)$, $\text{pk}(\pi) = |\text{Peak}(\pi)|$ the number of peaks.

Lemma 1.14. For $n, k \geq 1$,

$$W_{n,k} = (2k + 2)W_{n-1,k} + (n - 2k)W_{n-1,k-1}.$$

Proof. We have

$$\begin{aligned}
 D^n y &= D \sum_{k=0}^{\lfloor (n-2)/2 \rfloor} W_{n-1,k} z^{2k+2} y^{n-2k-2} \\
 &= \sum_{k=0}^{\lfloor (n-2)/2 \rfloor} (2k+2) W_{n-1,k} z^{2k+1} \cdot zy \cdot y^{n-2k-2} + (n-2k-2) W_{n-1,k} z^{2k+2} y^{n-2k-3} \cdot z^2 \\
 &= \sum_{k=0}^{\lfloor (n-2)/2 \rfloor} (2k+2) W_{n-1,k} z^{2k+2} y^{n-2k-1} + (n-2k-2) z^{2k+4} y^{n-2k-3}.
 \end{aligned}$$

The required follows. ■

Theorem 1.15.

$$W_n(x) = \sum_{\pi \in \mathfrak{S}_n} x^{\text{pk}(\pi)}.$$

Proof. Let Y_n be the polynomial on the right, and let $Y_{n,k}$ be its coefficients. It is easily checked that $Y_{n,k}$ and $W_{n,k}$ are equal for $n = 0$ or $k = 0$. To prove the statement, we shall merely show that $Y_{n,k}$ satisfies the recurrence of Lemma 1.14 too.

Similar to what we did in earlier proofs such as those of 1.2, 1.3, let σ be a permutation in \mathfrak{S}_{n-1} .

We shall use it to get a permutation $\pi \in \mathfrak{S}_n$ by “inserting” n at one of the n possible positions. If we insert it at the position of a non-peak of σ , the number of peaks increases by one. If we insert it before or after the position of a peak, the number of peaks stays the same. Since peaks cannot occur immediately after each other, we can insert it at precisely $2k+2$ positions while ensuring that the number of peaks does not increase (the extra 2 is for the extreme positions), and so at $n-2k-2$ positions which increases the number of peaks by one. Therefore,

$$Y_{n,k} = (2k+2)Y_{n-1,k} + (n-2(k-1)-2)Y_{n-1,k-1} = (2k+2)Y_{n-1,k} + (n-2k)Y_{n-1,k-1}.$$
■

1.6. Matching theory

Definition 1.8 (Matching). Given a graph $G = (V, E)$, a *matching* in G is a collection $M \subseteq E$ of edges such that for any distinct $e_1, e_2 \in M$, $e_1 \cap e_2 = \emptyset$.

The number of k -sized matchings is denoted $m_k(G)$. Define the *matching polynomial*

$$\text{Match}_G(x) = \sum_{k \geq 0} (-1)^k m_k(G) x^{n-2k}$$

Some books call the above the “defect” matching polynomial, taking the actual matching polynomial as $p(x) = \sum_k m_k(G) x^k$. Note that $\text{Match}_G(x) = x^n p(-1/x^2)$.

Clearly, $\text{Match}_G(x) = x^n \cdot p(-1/x^2)$.

There is a very rich literature regarding matching theory. One work that set off a frenzy of results in related areas was [Edm65], which gave a polynomial-time algorithm to get a maximum weight matching in any graph. It does so by looking at the polytope in \mathbb{R}^E that is the convex hull of the indicator functions of all matchings. It is worth noting that while there is a polynomial time algorithm to find a maximum weight matching, the problem of determining

the number of maximum matchings in a graph is #P-complete. Consequently, no polynomial time algorithm is known to determine $m_k(G)$ given a graph G .

Before moving on, we give some simple lemmas about the matching polynomial.

Lemma 1.16.

(a) If G and H are vertex-disjoint graphs,

$$\text{Match}_{G \cup H}(x) = \text{Match}_G(x) \text{Match}_H(x).$$

(b) Given a graph G and vertex $v \in G$,

$$\text{Match}_G(x) = x \text{Match}_{G-\{v\}}(x) - \sum_{u: u \leftrightarrow v} \text{Match}_{G-\{u,v\}}(x).$$

(c) Given a graph G and edge $e = \{u, v\} \in G$,

$$\text{Match}_G(x) = \text{Match}_{G-e}(x) - \text{Match}_{G-\{u,v\}}(x).$$

Proof. We omit the proof of (a) as it is straightforward.

(b) Let M be a matching of size k on G . If M does not have an edge incident on v , it is a matching of size k on $G - \{v\}$. Otherwise, there is some edge $e = \{u, v\} \in M$, and $M \setminus \{e\}$ is a matching on $G - \{u, v\}$. As a result,

$$m_k(G) = m_k(G - \{v\}) + \sum_{u: u \leftrightarrow v} m_{k-1}(G - \{u, v\}).$$

Multiplying with $(-1)^k x^{n-2k}$ and summing over k ,

$$\begin{aligned} \text{Match}_G(x) &= \sum_k (-1)^k x \cdot x^{(n-1)-2k} m_k(G - \{v\}) - \sum_{u: u \leftrightarrow v} (-1)^{k-1} x^{(n-2)-2(k-1)} m_{k-1}(G - \{u, v\}) \\ &= x \text{Match}_{G-\{v\}} - \sum_{u: u \leftrightarrow v} \text{Match}_{G-\{u,v\}}(x). \end{aligned}$$

(c) Similar to (b), let M be a matching of size k on G . If M does not have e , it is a matching of size k on $G - e$. Otherwise, $M \setminus \{e\}$ is a matching on $G - \{u, v\}$. So,

$$m_k(G) = m_k(G - e) + m_{k-1}(G - \{u, v\}).$$

Multiplying with $(-1)^k x^{n-2k}$ and summing over k ,

$$\begin{aligned} \text{Match}_G(x) &= \sum_k (-1)^k x^{n-2k} m_k(G - e) - (-1)^{k-1} x^{(n-2)-2(k-1)} m_{k-1}(G - \{u, v\}) \\ &= \text{Match}_{G-e}(x) - \text{Match}_{G-\{u,v\}}(x). \end{aligned} \quad \blacksquare$$

Proposition 1.17.

1. $m_k(P_n) = \binom{n-k}{k}$.
2. $m_k(C_n) = \frac{n}{n-k} \binom{n-k}{k}$.

3. $m_k(K_n) = \binom{n}{2k} \cdot \frac{(2k)!}{2^k k!}$.
4. $m_k(K_{n,n}) = \binom{n}{k}^2 k!$.

Proof.

1. Collapse every edge in a matching to its left endpoint, and “mark” the collapsed vertices. This results in a path with $n - k$ vertices with k marked vertices. This process of marking the vertices using the matching is reversible, and $m_k(G) = \binom{n-k}{k}$.
2. Fix some edge e . e is absent in exactly $(n - k)/n$ of the k -matchings of C_n . In this case, the remaining matching forms a matching on $C_n - e$, which is isomorphic to P_n . Therefore, $(n - k)/n m_k(C_n) = m_k(P_n) = \binom{n-k}{k}$.
3. A k -matching of K_n is obtained by choosing $2k$ vertices (done in $\binom{n}{2k}$) ways, putting the $2k$ vertices in k indistinguishable “boxes” by putting 2 in each (this can be done in $(2k)!/k!2^k$ ways).
4. A k -matching is obtained by choosing k vertices from each side of the bipartite graph (done in $\binom{n}{k}^2$ ways), then assigning each vertex on the left side a vertex on the right that it is joined to in the matching (done in $k!$ ways). ■

Theorem 1.18. Given a graph G , all roots of $\text{Match}_G(x)$ are real.

The version of the proof of the above we give is due to Godsil [GG81].

Proof. Using Lemma 1.16(a), we may assume that G is connected.

We first prove the result for the case where G is a tree T . To prove this, we shall prove that $\text{Match}_T(x)$ is the characteristic polynomial $\det(xI - A)$ of the adjacency matrix A of T (!); the result then follows since A is a real symmetric matrix and thus has real eigenvalues.

Let $xI - A = (b_{ij})$. We have

$$\text{Charpoly}(A) = \sum_{\pi \in \mathfrak{S}_n} \text{sign}(\pi) \prod_{i=1}^n b_{i\pi(i)}.$$

First, we claim that if $\pi \in \mathfrak{S}_n$ has a cycle of length greater than 2, then the term corresponding to π on the right will be zero. In other words, the term is zero if π is not an involution. Indeed, this follows immediately since G has no cycles (of length ≥ 3). As a result, if (i_1, i_2, \dots, i_t) were a cycle in π , then there must be some j such that $\{i_j, i_{j+1}\}$ is not an edge in G and $b_{i_j, i_{j+1}} = 0$.

Suppose that some $\pi \in \mathfrak{S}_n$ has k 2-cycles and $(n - 2k)$ fixed points, and also has the term on the right being nonzero. We have $\text{sign}(\pi) = (-1)^{(n - (k + n - 2k))} = (-1)^k$. Suppose that the k 2-cycles are $(i_1, j_1), (i_2, j_2), \dots, (i_k, j_k)$. We have $b_{i_r, j_r} = b_{j_r, i_r} = (-1)$ so $b_{i_r, j_r} b_{j_r, i_r} = 1$, and also that no i_r (or j_r) is equal to any other i_s (or j_s). That is, the edges constituted by $\{i_r, j_r\}$ form a matching of size k !. Therefore,

$$\text{Charpoly}(A) = \sum_{\substack{\pi \in \mathfrak{S}_n \\ \pi \text{ an involution}}} \text{sign}(\pi) \prod_{i=1}^n b_{i\pi(i)} = \sum_{\substack{\pi \in \mathfrak{S}_n \\ \pi \text{ an involution}}} (-1)^k x^{n-2k} = \sum_{\text{matchings } M} (-1)^{|M|} x^{n-2|M|} = \text{Match}_T(x).$$

For a general graph, we come up with a tree $T_a(G)$ that depends on a “starting vertex” $a \in G$. We then show that the matching polynomial of our graph divides the matching polynomial of the tree.

To define T_a , we need paths starting at a in G without repeated vertices. These paths are the vertices of $T_a(G)$. There is an edge between two paths if one is an extension of another by a single vertex – for example, the paths $abdc$ and $abdce$ would have an edge between them.

It is straightforward to see that G is isomorphic to $T_a(G)$ for any vertex $a \in G$ if G is a tree. Indeed, there is precisely one path from a to any vertex b in the tree. The heart of the argument is the fact that for any $a \in G$,

$$\frac{\text{Match}_{G-a}(x)}{\text{Match}_G(x)} = \frac{\text{Match}_{T_a(G)-a}(x)}{\text{Match}_{T_a(G)}(x)}. \quad (1.3)$$

To prove this, we use induction on the number of vertices n . The base case is $n = 2$, which forces G to be a tree. Now,

$$\begin{aligned} \frac{\text{Match}_G(x)}{\text{Match}_{G-a}(x)} &= \frac{x \text{Match}_{G-a}(x) - \sum_{b \leftrightarrow a} \text{Match}_{G-a-b}(x)}{\text{Match}_{G-a}(x)} \\ &= x - \sum_{b \leftrightarrow a} \frac{\text{Match}_{G-a-b}(x)}{\text{Match}_{G-a}(x)}. \end{aligned}$$

By the inductive hypothesis,

$$\frac{\text{Match}_{G-a-b}(x)}{\text{Match}_{G-a}(x)} = \frac{\text{Match}_{T_b(G-a)-b}(x)}{\text{Match}_{T_b(G-a)}(x)}. \quad (1.4)$$

Now, very carefully observe that

$$\begin{aligned} T_b(G-a) - b &= \bigcup_{\substack{c \leftrightarrow b \\ c \neq a}} T_c(G-a) \\ T_a(G) - a &= \bigcup_{c \leftrightarrow a} T_c(G-a) \\ T_a(G) - a - ab &= \left(\bigcup_{\substack{c \leftrightarrow a \\ a \neq b}} T_c(G-a) \right) \cup \left(\bigcup_{\substack{c \leftrightarrow b \\ c \neq a}} T_c(G-a-b) \right) = \left(\bigcup_{\substack{c \leftrightarrow a \\ a \neq b}} T_c(G-a) \right) \cup (T_b(G-a) - b) \end{aligned}$$

We can then use Lemma 1.16(a) to get that

$$\begin{aligned} \text{Match}_{T_a(G)-a}(x) &= \prod_{c \leftrightarrow a} \text{Match}_{T_c(G-a)}(x). \\ \text{Match}_{T_a(G)-a-ab}(x) &= \prod_{\substack{c \leftrightarrow a \\ c \neq b}} \text{Match}_{T_c(G-a)}(x) \times \text{Match}_{T_b(G-a)-b}(x). \end{aligned}$$

Dividing the two,

$$\frac{\text{Match}_{T_a(G)-a-ab}(x)}{\text{Match}_{T_a(G)-a}(x)} = \frac{\text{Match}_{T_b(G-a)-b}(x)}{\text{Match}_{T_b(G-a)}(x)}. \quad (1.5)$$

Combining Equations (1.4) and (1.5),

$$\frac{\text{Match}_{G-a-b}(x)}{\text{Match}_{G-a}(x)} = \frac{\text{Match}_{T_a(G)-a}(x)}{\text{Match}_{T_a(G)-a-ab}(x)}$$

and

$$\begin{aligned} \frac{\text{Match}_G(x)}{\text{Match}_{G-a}(x)} &= x - \sum_{b \leftrightarrow a} \frac{\text{Match}_{T_a(G)-a-ab}(x)}{\text{Match}_{T_a(G)-a}(x)} \\ &= \frac{x \text{Match}_{T_a(G)-a}(x) - \sum_{b \leftrightarrow a} \text{Match}_{T_a(G)-a-ab}(x)}{\text{Match}_{T_a(G)-a}(x)} \\ &= \frac{\text{Match}_{T_a(G)}(x)}{\text{Match}_{T_a(G)-a}(x)}. \end{aligned} \quad (\text{by Lemma 1.16(b)})$$

Now, to complete the proof, we shall show that $\text{Match}_{T_a(G)}(x)$ divides $\text{Match}_G(x)$. We do so by induction. To do this, by Equation (1.3), it suffices to show that $\text{Match}_{G-a}(x)$ divides $\text{Match}_{T_a(G)-a}(x)$. Recalling that $T_a(G) - a = \bigcup_{b \leftrightarrow a} T_b(G-a)$, the inductive hypothesis implies that $\text{Match}_{G-a}(x)$ divides each $\text{Match}_{T_b(G-a)}(x)$, so divides their product $\text{Match}_{T_a(G)-a}(x)$ as well, completing the proof. \blacksquare

This result has some consequences.

Definition 1.9 (Log-concave). A sequence $(a_n)_{n \geq 0}$ is said to be *log-concave* if $a_n^2 \geq a_{n-1}a_{n+1}$ for all n .

Exercise 1.6. Show that for a fixed n , $\binom{n}{k}$ as k varies is log-concave.

The Stirling numbers of the first and second kind are also log-concave.

Proposition 1.19. If $A(x) = \sum_{i=0}^n a_i x^i$ is a polynomial with all real roots, then the sequence of coefficients of A is log-concave.

Exercise 1.7. Prove the above.

The above has an even stronger version.

Proposition 1.20. If $A(x) = \sum_{i=0}^n a_i x^i$ is a polynomial with all real roots, then $\left(a_i / \binom{n}{i}\right)_{i \geq 0}$ is log-concave. This is referred to as *ultra-logconcavity*.

Corollary 1.21. For any graph G , $(m_k(G))_{k \geq 0}$ is log-concave. That is, for all k , $m_k(G)^2 \geq m_{k-1}(G)m_{k+1}(G)$.

1.7. Colorings

Definition 1.10. Given a graph $G = (V, E)$, a k -coloring (sometimes called *proper coloring*) is a function $c : V(G) \rightarrow [k]$ such that if $u \leftrightarrow v$, $c(u) \neq c(v)$.

The *chromatic number* $\chi(G)$ of a graph is the minimum number of colours required to colour it. We denote by $c_k(G)$ the number of k -colorings of G .

Determining the chromatic number of a graph is (or rather, determining if there exists a k -coloring) is NP-hard. The best known algorithm today outputs a colouring which is a $n/\text{polylog}(n)$ -approximation of the minimum coloring.

Proposition 1.22. A graph G has chromatic number 1 iff it is an empty graph. It has chromatic number ≤ 2 iff it is bipartite.

It is difficult to approximate a minimum colouring of even 3-colorable graphs!

Theorem 1.23 (Four-Color Theorem, [AH89]). A planar graph is 4-colorable.

We omit the proof of the above (for reasons obvious to anyone familiar with the result).

Theorem 1.24. For any graph G , there exists a polynomial Chrom_G , known as the *chromatic polynomial*, such that $\text{Chrom}_G(k) = c_k(G)$.

For example, $\text{Chrom}_{\overline{K_n}}(x) = x^n$. For any tree T on n vertices, $\text{Chrom}_T(x) = t(t-1)^{n-1}$.

Observe that the chromatic polynomial is unique for a given graph since we know its value at an infinite number of points.

The proof of the above follows near-directly from the following result using an inductive argument on the number of edges – both $G \setminus e$ and $G - e$ have fewer edges than G .

Proposition 1.25 (Deletion-contraction recurrence). For any graph G , we have for $e \in G$ that

$$\text{Chrom}_G(x) = \text{Chrom}_{G-e}(x) - \text{Chrom}_{G \setminus e}(x)$$

Proof. Take any k -coloring of $G - e$. If the endpoints of e have the same colour, it corresponds to a k -colouring of $G \setminus e$, and if the endpoints have distinct colours, it corresponds to a k -coloring of G . Therefore,

$$c_k(G) = c_k(G - e) - c_k(G \setminus e)$$

and the result follows. ■

This leads to a method to find the chromatic polynomial of any graph. Since we know the chromatic polynomial of the empty graph, we can repeatedly delete and contract edges until from our graph until we get to an empty graph. A natural question based on what we've done so far is: what do the coefficients of the chromatic polynomial mean?

Definition 1.11. Let $G = (V, E)$ be a graph and $<$ a total order on E . Given a cycle C , the corresponding *broken circuit* B is given by $E(C) \setminus \{e\}$, where e is the smallest edge in $E(C)$ in the total order. A set A of edges is said to be an *NBC set* (no broken circuit) if $B \not\subseteq A$ for any broken circuit B . Also let

$$\text{NBC}_k(G) = \{A \subseteq E : |A| = k \text{ and } A \text{ is an NBC set}\}$$

and $\text{nbc}_k(G) = |\text{NBC}_k(G)|$.

Theorem 1.26. If $|V| = n$, then for any ordering of E ,

$$\text{Chrom}_G(t) = \sum_{k=0}^n (-1)^k \text{nbc}_k(G) t^{n-k}.$$

Proof. Fix some t . For each $A \in \text{NBC}_k(G)$, consider the corresponding subgraph with edge set A . This describes a forest on V with $n - k$ components. The number of functions $c : V \rightarrow [t]$ such that c is constant on components of A is t^{n-k} . Call such a coloring an A -improper coloring. For each such pair (A, c) , assign the sign $\text{sign}(A, c) = (-1)^k$. Denote the set of all such pairs by S .

We would like to show that

$$\sum_{(A,c) \in S} (-1)^{\text{sign}(A)} = \text{Chrom}_G(t) = c_t(G).$$

Observe that $(\emptyset, c) \in S$ for any proper coloring c , so it suffices to show that the summation of the remaining terms is 0. Call this set of remaining terms S' . We shall come up with a sign-reversing involution ι on S' to prove that the sum of signs is 0.

Observe that given any $(A, c) \in S'$, there must exist edges that are monochromatic. Let e be the smallest such edge, and let $\iota(A, c) = (A \triangle \{e\}, c) = (A', c)$. It is evident that ι is sign-reversing, and it is an involution because c does not change, so the smallest monochromatic edge e does not either. We are done if we manage to show that the expression on the right is indeed in S .

If $A' = A \setminus \{e\}$, then it is clearly an NBC set and the coloring is A' -improper (since it is A -improper). If $A' = A \cup \{e\}$, since e joined two vertices of the same color, c is A' -improper. Suppose instead that A' is not an NBC set. Then, it contains a broken circuit B such that $e \in B$. Let C be the cycle causing B to be a broken circuit. Because c is A' -improper, all vertices in C have the same colour. However, e is the smallest monochromatic edge in C , contradicting the fact that a smaller edge was removed to get B and completing the proof. ■

Corollary 1.27. Chrom_G is a monic polynomial with coefficients of alternating sign.

Another question (that is not so natural) is: is $\text{Chrom}_G(x)$ meaningful for $x \notin \mathbb{N}$?

Definition 1.12. Given a graph $G = (V, E)$, an *acyclic orientation* of G is obtained by replacing each edge uv with one of the directed arcs \overrightarrow{uv} or \overleftarrow{uv} .

Theorem 1.28. $\text{Chrom}_G(-1) = (-1)^n a(G)$, where $n = |V(G)|$ and $a(G)$ is the number of acyclic orientations of G .

Also observe that by Theorem 1.26, $a(G)$ is equal to the number of NBC sets in G .

Proof. Let $e = \{u, v\}$ be an arbitrary edge in the graph. Using the **Deletion-contraction recurrence**, it suffices to show that

$$a(G) = a(G - e) + a(G \setminus e).$$

Let $A(G)$ be the set of acyclic orientations on G , so $a(G) = |A(G)|$.

Define $f : A(G) \rightarrow A(G - e)$ as the natural restriction map. We claim that f is surjective.

Suppose instead that some $O' \in A(G - e)$ is not in the image of f . Consider the two orientations O_1, O_2 which are identical to O' except that the edge e has orientation $u \rightarrow v$ or $v \rightarrow u$ respectively. Since neither of these is in $A(G)$, there must be a directed path $v \rightarrow u$ in O' (because O_1 has a cycle) and another directed path $u \rightarrow v$ in O' (because O_2 has a cycle). Concatenating the two, we get a directed closed walk which must contain a cycle, contradicting the fact that $O' \in A(G - e)$.

Because f is a restriction map, for any $O' \in A(G - e)$, $|f^{-1}(O')| \in \{1, 2\}$. Let X and Y be the set of all O' with $|f^{-1}(O')| = 1$ and $|f^{-1}(O')| = 2$ respectively. Also let $x = |X|$ and $y = |Y|$.

We have $a(G - e) = x + y$ and $a(G) = x + 2y$, so we are done if we show that $a(G \setminus e) = y$.

Because we can orient e in either way for any $O' \in A(G - e)$ to get an orientation in $A(G)$, there is no directed path from u to v or v to u in O' . In particular, when merging u and v in O' to get an orientation of $A(G \setminus e)$, there is no issue in assigning orientations (there cannot be a vertex w such that \overrightarrow{uw} and \overrightarrow{vw} are edges).

This merging procedure can be reversed as well, so there is a bijection between Y and $A(G \setminus e)$ and we are done. ■

This idea of plugging negative values into polynomials of interest has led to the fascinating subject of combinatorial reciprocity. This includes the idea of “running recurrences backward”. For example, we have the Fibonacci numbers defined by $f_0 = 0$, $f_1 = 1$, and $f_{n+1} = f_n + f_{n-1}$. Can we extend this to negative numbers such that $f_{m-1} = f_{m+1} - f_m$,

where $m - 1$ is negative. This leads to a signed version of the Fibonacci numbers, with $f_{-n} = (-1)^{n+1} f_n$ for $n > 0$.

We encourage the reader to try Problem 2.3.5 to get that on running the binomial recurrence backwards (for negative n), one gets

$$\binom{-(n+1)}{k} = (-1)^k \binom{n+k}{k}.$$

Exercise 1.8. Run the recurrence of $S_{n,k}$ backwards (to negative n, k).

The interested reader may refer to [BS] for more details on reciprocity theorems.

1.8. Increasing spanning forests

Definition 1.13 (Increasing spanning forest). Let $G = (V, E)$ and let the elements of V be totally ordered. Let F be a forest in G . Root each connected component T of F at its minimum vertex. F is called an *increasing spanning forest* if each tree is increasing, that is, the “children” of any vertex in the tree with respect to the rooting are larger than the vertex. Equivalently, any path from a root to a vertex in the tree is increasing.

Let $\text{isf}_m(G)$ be the number of increasing spanning forests on G with m edges, and define

$$\text{ISF}_G(x) = \sum_{m \geq 0} (-1)^m \text{isf}_m(G) x^{n-m}.$$

Lemma 1.29. Let $G = (V = [n], E)$ with the total order on V being the natural order. For each $k \in V$, let

$$E_k = \{\{i, k\} \in E : i < k\}.$$

F is an increasing spanning forest of G iff it has at most one edge from each E_k .

Observe that the E_k are mutually disjoint and their union is all of E .

Proof. Suppose that there are two edges $\{i, k\}$ and $\{j, k\}$ in some E_k in an isf F , where $i < j$. Then, the root of the tree containing $\{i, j, k\}$ is at most i . In particular, one of the paths from this root to i or j must contain the subpath ikj or jki , which contradicts the fact that it is increasing.

On the other hand, let $F \subseteq E$ such that $|F \cap E_k| \leq 1$ for each k .

First, let us show that F is acyclic. Suppose instead that $v_1 v_2 \cdots v_r v_1$ is a cycle, and let $v_j = \max_{1 \leq i \leq r} v_i$. Then, both $v_{j-1} v_j$ and $v_{j+1} v_j$ are edges in E_{v_j} , contradicting the fact that $|F \cap E_{v_j}| \leq 1$.

Now, we must show that it is increasing. Suppose instead that $v_1 v_2 \cdots v_r$ is a non-increasing path in F , with $v_1 \leq v_i$ for $i > 1$, and that $v_{j-1} < v_j > v_{j+1}$. This again contradicts the fact that $|F \cap E_{v_j}| \leq 1$, completing the proof. ■

Theorem 1.30. With E_i defined as above,

$$\text{ISF}_G(x) = \sum_{i=1}^n (x - |E_i|).$$

Proof. Let the polynomial on the right be p . Then, the coefficient of x^{n-m} in p is

$$\sum_{\{i_1, \dots, i_m\} \subseteq [n]} |E_{i_1}| |E_{i_2}| \cdots |E_{i_m}|.$$

This is precisely equal to $\text{isf}_m(G)$ by Lemma 1.29. ■

It has been observed that for certain classes of graphs and orderings, this is equal to the chromatic polynomial – the interested reader may look at [Sag20] for more details.

1.9. Linear recurrences and rational generating functions

Consider sequences (a_n) such that

$$A(x) = \sum a_n x^n = \frac{p(x)}{q(x)},$$

where q is a polynomial of degree d and p is a polynomial of degree $< d$.

Definition 1.14. A sequence $(a_n)_{n \geq 0}$ of reals is said to satisfy a *linear constant term recurrence* (of length d) if there exist complex numbers c_1, \dots, c_d with $c_d \neq 0$ such that

$$a_{n+d} + c_1 a_{n+d-1} + \cdots + c_d a_n = 0$$

for all $n \geq 0$.

A simple example of this is the recurrence satisfied by the Fibonacci numbers. Given $f_{n+2} - f_{n+1} - f_n = 0$, the recurrence is

$$F(x) = \frac{p(x)}{1 - x - x^2},$$

where p depends on the initial values. Observe that the coefficients $1, -1, -1$ in the denominator match those in the recurrence!

Theorem 1.31. Let $(a_n)_{n \geq 0}$ be a sequence with generating function A . The following are equivalent.

- (a) $(a_n)_{n \geq 0}$ satisfies a linear constant term recurrence of length d with constants c_1, \dots, c_d .
- (b) There exist

$$A(x) = \sum a_n x^n = \frac{p(x)}{q(x)},$$

where $q(x) = 1 + c_1 x + \cdots + c_d x^d$ and $\deg(p) < d$.

- (c) If the roots of the polynomial q in (b) are $(1/r_i)_{i=1}^k$, with $(1/r_i)$ having multiplicity d_i , then there are polynomials $(p_i)_{i=1}^k$ of degree $< d_i$ such that

$$a_n = \sum_{i=1}^k p_i(n) \alpha_i^n$$

for all $n \geq 0$.

Proof.

(a) \Rightarrow (b) Multiply the linear constant term recurrence by x^{n+d} and sum over all $n \geq 0$. Setting $c_0 = 1$, we get

$$0 = \sum_{t=0}^d c_t x^t \left(A(x) - \sum_{i=1}^{d-t-1} a_i x^i \right),$$

so

$$A(x) = \frac{\sum_{t=0}^d c_t x^t \left(\sum_{i=1}^{d-t-1} a_i x^i \right)}{\sum_{t=0}^d c_t x^t} = \frac{p(x)}{q(x)},$$

where $\deg(p) < d$.

(b) \Rightarrow (a) We have $q(x)A(x) = p(x)$. Because $\deg(p) < d$, the coefficient of x^{n+d} on the right hand side is zero. On the left, this coefficient is precisely equal to the left hand side of the desired recurrence.

(b) \Leftrightarrow (c) Let us check that (b) implies (c) first. We have

$$A(x) = \frac{p(x)}{\prod_{i=1}^k (1 - r_i x)^{d_i}}.$$

Checking that (c) holds true amounts to expanding the denominator to the numerator and matching coefficients. The argument is reversible as well, so (c) implies (b). ■

Also observe that running a linear constant term recurrence backwards (extending it to negative n) gives another linear constant term recurrence!

Theorem 1.32. Let $(a_n)_{n \geq 0}$ be a sequence satisfying a linear constant term recurrence. Obtain $a(-n)$ by running the recurrence backwards, and set

$$A^{\text{rev}}(x) = \sum_{n \geq 1} a(-n) x^n.$$

Then,

$$A^{\text{rev}}(x) = -A\left(\frac{1}{x}\right).$$

Proof. ■

There are numerous multivariate extensions of this done by Stanley.

1.10. Exponential Generating Functions

Definition 1.15. Given a sequence $(a_n)_{n \geq 0}$, its *exponential generating function* (egf) is defined by

$$A(x) = \sum_{n \geq 0} \frac{a_n x^n}{n!}.$$

Lemma 1.33. If $A(x)$ and $B(x)$ are the egfs of (a_n) and (b_n) respectively, then $A(x)B(x)$ is the egf of $(c_n)_{n \geq 0}$ defined by

$$c_n = \sum_{k=0}^n \binom{n}{k} a_k b_{n-k}.$$

The above is very simple to prove, and we omit the proof.

Let us use the above to determine the egf for d_n , the number of derangements in \mathfrak{S}_n . Take by convention that $d_0 = 1$.

Proposition 1.34. It is true that

$$\sum_{k=0}^n \binom{n}{k} d_{n-k} = n!.$$

Proof. Given a bijection $\pi \in \mathfrak{S}_n$, let $S \subseteq [n]$ be the set of fixed points $\{i : \pi_i = i\}$ of the permutation. This results in a derangement of $[n] \setminus S$, and this idea results in a bijection between

$$\mathfrak{S}_n \text{ and } \{(S, \sigma) : S \subseteq [n], \sigma \text{ is a derangement of } [n] \setminus S\}.$$

■

Corollary 1.35. The egf of $(d_n)_{n \geq 0}$ is equal to

$$D(x) = \frac{1}{e^x(1-x)}.$$

Proof. By the previous proposition,

$$n! = \sum_{k=0}^n \binom{n}{k} \cdot d_{n-k} \cdot 1.$$

The egf of the constant sequence 1 is e^x and the egf of $(n!)$ is $1/(1-x)$. By Lemma 1.33, $D(x)e^x = 1/(1-x)$, completing the proof. ■

Proposition 1.36. If $(a_n)_{n \geq 0}$ has egf $A(x)$, then

$$A'(x) = \sum_{n \geq 0} a_n \frac{x^{n-1}}{(n-1)!}.$$

We now encourage the reader to do Problem 2.3.1.

1.11. Another pair of parameters with equal statistics

Recall how we had seen in Proposition 1.3 a pair of parameters that have the same distribution. Now, we shall look at another such pair of parameters.

Recall descents in \mathfrak{S}_n from Definition 1.3.

Definition 1.16 (Eulerian polynomial). Define the *Eulerian polynomial*

$$A_n(t) = \sum_{\pi \in \mathfrak{S}_n} t^{\text{des}(\pi)}. \quad (1.6)$$

For example, $A_3(t) = 1 + 4t + t^2$. Let $A_{n,k}$ be the coefficient of x^k in A_n – this is the number of $\pi \in \mathfrak{S}_n$ with $\text{des}(\pi) = k$. One gets the recurrence

$$A_{n,k} = (k+1)A_{n-1,k} + (n-k)A_{n-1,k-1}$$

for $n \geq 1$ with $A_{0,0} = 1$. This may be proved by the (hopefully) now standard trick of seeing how the number of descents changes on inserting $n+1$ at various positions in $\pi \in \mathfrak{S}_n$.

Exercise 1.9. Prove the above.

Also observe that on reversing a permutation, we have $\text{des}(\pi^{\text{rev}}) = (n-1) - \text{des}(\pi)$. This means that the coefficients of A_n are palindromic. Further, descents and “ascents” are equidistributed.

Definition 1.17 (Excedances). Given $\pi \in \mathfrak{S}_n$, define the set of *excedances*

$$\text{EXC}(\pi) = \{i \in [n] : \pi_i > i\}$$

and the number of excedances $\text{exc}(\pi) = |\text{EXC}(\pi)|$.

Excedances are something of a cyclic counterpart of descents.

Theorem 1.37. Descents and excedances are equidistributed.

Proof. Let $\pi \in \mathfrak{S}_n$ have cycles c_1, \dots, c_k . For each i , let m_i be the maximal element of c_i , and assume that c_i is written starting with m_i . Also assume that we write the cycles in increasing order of m_i . We refer to this as the *canonical* cycle decomposition of π . Suppose we write the permutation in this form, as

$$((c_1)_1(c_1)_2 \cdots (c_1)_{r_1}) \cdots ((c_k)_1(c_k)_2 \cdots (c_k)_{r_k}).$$

Observe that the parenthesising is redundant! Reading the string $(c_1)_1(c_1)_2 \cdots (c_1)_{r_1} \cdots (c_k)_1(c_k)_2 \cdots (c_k)_{r_k}$ from left to right, we can recover the cycles (how?). This gives an explicit bijection between canonical cycle representations and \mathfrak{S}_n . ■

Consider a *palindromic polynomial*

$$f(t) = f_0 + f_1 t + \cdots + f_d t^d,$$

where $f_r = f_{d-r}$. Let k be the “center of palindromicity” which is roughly $d/2$. For a fixed d , observe that the sum of palindromic polynomials is palindromic, and the scalar multiple of a palindromic polynomial is palindromic as well. That is, the set of palindromic polynomials form a vector space.

One obvious basis of this vector space is

$$\{t^r + t^{d-r} : 0 \leq r \leq k\}.$$

Another (less obvious) basis of this space is

$$\{t^j(1+t)^{d-2j} : 0 \leq j \leq k\}.$$

This is referred to as the *Gamma basis* – why is it a basis?

Theorem 1.38 ([?]). The Eulerian polynomial is γ -positive.

That is, when the Eulerian polynomial is represented as a linear combination of the elements of the Gamma basis, all coefficients are positive. For example,

$$A_5(t) = 1 + 26t + 66t^2 + 26t^3 + t^4 = (1+t)^4 + 22t(1+t)^2 + 16t^2.$$

We do not prove the above.

Similar to excedances, consider non-excedances – points where $\pi_i < i$.

Exercise 1.10. Show that $\text{exc}(\pi) = \text{nonexc}(\pi^{-1})$.

§2. Problem Sheets

2.1. Problem Sheet 1

Problem 2.1.1. Let $S(n, k)$ and $s(n, k)$ be Stirling numbers of the second and first kind respectively. Show that for all n, k , we have $s(n, k) \geq S(n, k)$.

Solution

Let $X_{S(n,k)}$ be the set of partitions of $[n]$ into exactly k parts and $X_{s(n,k)}$ the number of permutations of $[n]$ with exactly k cycles. Recall that by definition, $|X_{S(n,k)}| = S(n, k)$ and $|X_{s(n,k)}| = s(n, k)$. It suffices to demonstrate an injection f from $X_{S(n,k)}$ to $X_{s(n,k)}$. We do so as follows. Let $\{\{x_{1,1}, \dots, x_{1,n_1}\}, \dots, \{x_{k,1}, \dots, x_{k,n_k}\}\}$ be a partition of $[n]$ into exactly k parts, where $x_{i,j_1} < x_{i,j_2}$ for $j_1 < j_2$. Then, we have a corresponding permutation of $[n]$ with exactly k cycles given by $(x_{1,1}, \dots, x_{1,n_1}) \cdots (x_{k,1}, \dots, x_{k,n_k})$. This map is clearly an injection, so we are done.

Problem 2.1.2. Show that

$$S(n, k) = \sum_{r=1}^k (-1)^{k-r} \frac{r^n}{r!(k-r)!}.$$

Solution

$S(n, k)$ is merely $1/k!$ times the number of surjective functions from $[n]$ to $[k]$ (because the ordering of the partitions does not matter). The set of functions that are *not* surjective is

$$\bigcup_{i \in [n]} \{f \in [k]^{[n]} : i \notin \text{Im}(f)\}.$$

The size of the above is quite easily determined by the inclusion-exclusion principle to get

$$k^n - k!S(n, k) = \sum_{r=1}^{k-1} (-1)^{r+1} \cdot \underbrace{\binom{k}{r}}_{\text{choosing } r \text{ elements in } [k] \text{ to "avoid" }} \cdot \underbrace{(k-r)^n}_{\text{counting functions that avoid the chosen}},$$

and the desideratum immediately follows.

Problem 2.1.3. Let $A_n(y) = \sum_k S(n, k)y^k$. Show that $A_n(y) = (y + yD)^n 1$ where $D = \frac{d}{dy}$ is the derivative operator.

Solution

First, recall that $S(n+1, k+1) = S(n, k) + (k+1) \cdot S(n, k+1)$ – the $S(n, k)$ corresponds of those partitions where $n+1$ is in a part of its own, and the $(k+1)S(n, k+1)$ corresponds to those partitions where this is not the case, so we can consider any partition of $[n]$ into $k+1$ parts, then decide which of the $k+1$ parts to place $n+1$ in.

We have

$$\begin{aligned}
 (y + yD)A_n(y) &= (y + yD) \sum_{k=1}^n S(n, k)y^k \\
 &= \sum_{k=1}^n S(n, k)(y^{k+1} + ky^k) \\
 &= S(n, 1)y + \sum_{k=2}^n y^k (S(n, k-1) + (k-1)S(n, k)) + S(n, n)y^{n+1} \\
 &= S(n+1, 1)y + \sum_{k=2}^n S(n+1, k)y^k + S(n+1, n+1)y^{n+1} = A_{n+1}(y).
 \end{aligned}$$

The required follows inductively.

Problem 2.1.4. Let D_n be the number of derangements in \mathfrak{S}_n and let $D(x) = \sum_{n \geq 0} D_n x^n / n!$ be its egf. Determine $D(x)$.

Solution

A permutation $\pi \in \mathfrak{S}_n$ is a derangement iff it has no cycles of length 1. Define $f : \mathbb{N} \rightarrow \mathbb{N}_0$ by

$$f(k) = \begin{cases} 0, & k = 1, \\ 1, & \text{otherwise.} \end{cases}$$

By the earlier observation, $\pi \in \mathfrak{S}_n$ is a derangement iff $f(|C_1|) \cdots f(|C_k|) = 1$ where C_1, \dots, C_k are the cycles of π . Using Corollary 5.1.9 in [SF99], we get that

$$D(x) = \exp \left(\sum_{n \geq 2} \frac{x^n}{n} \right) = \exp(-x - \log(1-x)) = \frac{e^{-x}}{1-x}.$$

Problem 2.1.5. Let $s(n, 2)$ denote the number of $\pi \in \mathfrak{S}_n$ with 2 cycles in its cyclic decomposition and let H_n denote the n th harmonic number. Show that $s(n+1, 2) = H_n \times n!$.

Solution

It is easily checkable that the number of cyclic permutations of $[k]$ is $(k-1)!$. We have

$$\begin{aligned}
 s(n+1, 2) &= \sum_{k=1}^{\lfloor (n+1)/2 \rfloor} \binom{n+1}{k} (k-1)!(n+1-k-1)! \\
 &= \sum_{k=1}^{\lfloor (n+1)/2 \rfloor} \frac{(n+1)!}{k(n+1-k)} \\
 &= \sum_{k=1}^{\lfloor (n+1)/2 \rfloor} n! \left(\frac{1}{k} + \frac{1}{n+1-k} \right) \\
 &= n! \left(\sum_{k=1}^{\lfloor (n+1)/2 \rfloor} \frac{1}{k} + \sum_{k=\lceil (n+1)/2 \rceil}^n \frac{1}{k} \right) \\
 &= \begin{cases} n!H_n, & n \text{ is even,} \\ n!(H_n + \frac{2}{n+1}), & n \text{ is odd.} \end{cases}
 \end{aligned}$$

Problem 2.1.6. For a fixed positive integer k , consider the egf $f_k(x) = \sum_{n \geq 0} s(n, k)x^n/n!$. Show that

$$f_k(x) = \frac{1}{k!} \ln \left(\frac{1}{1-x} \right)^k.$$

Solution

Define $g : \mathbb{N} \rightarrow \mathbb{N}_0$ by

$$g(r) = \begin{cases} 1, & r = k, \\ 0, & \text{otherwise.} \end{cases}$$

Observe that

$$s(n, k) = \sum_{\pi \in \mathfrak{S}_n} g(r),$$

where C_1, \dots, C_r are the cycles in π . We now use Corollary 5.1.8 in [SF99] with f being the function that takes the constant 1. We have $E_g(x) = \frac{1}{k!}x^k$, so we get that

$$f_k(x) = \frac{1}{k!} \left(\sum_{n \geq 1} \frac{x^n}{n} \right)^k = \frac{1}{k!} \ln \left(\frac{1}{1-x} \right)^k.$$

Problem 2.1.7. Find $\sum_{k=0}^n (-1)^k s(n, k)$.

Solution

Recall that a permutation in \mathfrak{S}_n with k cycles has sign $(-1)^{n-k}$. We have

$$\begin{aligned} \sum_{k=0}^n (-1)^k s(n, k) &= \sum_{k=0}^n \sum_{\substack{\pi \in \mathfrak{S}_n \\ \pi \text{ has exactly } k \text{ cycles}}} (-1)^k \\ &= (-1)^n \sum_{\pi \in \mathfrak{S}_n} \text{sign}(\pi). \end{aligned}$$

For $n = 1$, this is -1 . Otherwise, note that $\pi \mapsto (1, 2)\pi$ is a bijection between odd and even permutations. As a result, the above sum is equal to 0.

Problem 2.1.8. Show that $S(n+1, k+1) = \sum_{m=0}^n \binom{n}{m} S(m, k)$.

Solution

We shall count the partitions of $[n+1]$ into exactly $k+1$ parts based on the part $n+1$ is in. We have

$$S(n+1, k+1) = \sum_{T \subseteq [n]} S([n] \setminus T, k) = \sum_{m=0}^n \binom{n}{m} S(n-m, k) = \sum_{m=0}^n \binom{n}{m} S(m, k).$$

Problem 2.1.9. Show that for $n \geq 1$, the $S_{n,k}$ as k varies has either a unique maximum value or has at most two equal values.

Solution

2.2. Problem Sheet 2

Problem 2.2.1. Show that

- (a) $T_n(1) = 1$ and
 (b) $T_n(-1) = (-1)^n$.

Solution

This immediately follows since $T_n(\cos \theta) = \cos n\theta$, so $T_n(\cos 0) = \cos(n \cdot 0) = 1$ and $T_n(\cos \pi) = \cos(n\pi) = (-1)^n$. They can also be easily proved inductively.

Problem 2.2.2. Show that

- (a) $U_n(1) = n + 1$.
 (b) $U_n(-1) = (-1)^n(n + 1)$

Solution

We prove this inductively. Both statements are trivially true for $n = 0, 1$. For $n \geq 2$, inductively, we have

$$U_n(1) = 2U_{n-1}(1) - U_{n-2}(1) = 2n - (n - 1) = n + 1$$

and

$$U_n(-1) = -2U_{n-1}(1) - U_{n-2}(1) = (-1)^n \cdot 2n + (-1)^{n-1}(n - 1) = (-1)^n(n + 1).$$

Problem 2.2.3. Show that

$$\frac{1}{\iota^n} U_n(\iota/2) = f_{n+1}.$$

Solution

Again, we prove this inductively. We have $U_0(\iota/2) = 1 = f_1$ and $U_1(\iota/2) = \iota = \iota f_2$. For $n \geq 2$, we inductively have

$$U_n(\iota/2) = \iota U_{n-1}(\iota/2) - U_{n-2}(\iota/2) = \iota^n f_n - \iota^{n-2} f_{n-1} = \iota^n (f_n + f_{n-1}) = \iota^n f_{n+1}.$$

Problem 2.2.4. Show that if $m, n \geq 1$,

$$T_{m+n}(x) = T_m(x)U_n(x) - T_{m-1}(x)U_{n-1}(x).$$

Solution

This may be checked manually for $m + n = 2, 3$. We perform induction on $m + n$. We have that

$$\begin{aligned} T_{m+n}(x) &= 2xT_{m+n-1}(x) - T_{m+n-2}(x) \\ &= 2x(T_{m-1}(x)U_n(x) - T_{m-2}(x)U_{n-1}(x)) - (T_{m-1}(x)U_{n-1}(x) - T_{m-2}(x)U_{n-2}(x)) \\ &= 2xT_{m-1}(x)U_n(x) - T_{m-1}(x)U_{n-1}(x) - T_{m-2}(x)(2xU_{n-1}(x) - U_{n-2}(x)) \\ &= 2xT_{m-1}(x)U_n(x) - T_{m-1}(x)U_{n-1}(x) - T_{m-2}(x)U_n(x) \\ &= U_n(x)(2xT_{m-1}(x) - T_{m-2}(x)) - T_{m-1}(x)U_{n-1}(x) \\ &= T_m(x)U_n(x) - T_{m-1}(x)U_{n-1}(x). \end{aligned}$$

2.3. Problem Sheet 3

Problem 2.3.1. Let (E_n) be the Euler numbers – E_n is the number of **alternating permutations** of $[n]$. Show that its egf

$$E(x) = \sum_{n \geq 0} E_n \frac{x^n}{n!} = \sec x + \tan x.$$

Solution

Let $n \geq 1$. Suppose that $n + 1$ is at the $(k + 1)$ th position of an alternating permutation in \mathfrak{S}_{n+1} for some odd k . The section before this as well as the section after this must be equal to the alternating permutations of some subset (of size k or $n - k$) of $[n]$. Consequently,

$$E_{n+1} = \sum_{\substack{k \in [n]_0 \\ k \text{ odd}}} \binom{n}{k} E_k E_{n-k}.$$

Repeating the same activity but considering the placement of 1 instead (observe that the number of “reverse-alternating” permutations which start with a decrease instead of an increase is equal to the number of alternating permutations) gives that

$$E_{n+1} = \sum_{\substack{k \in [n]_0 \\ k \text{ even}}} \binom{n}{k} E_k E_{n-k}.$$

Therefore,

$$\begin{aligned} 2E_{n+1} &= \sum_{k=0}^n \binom{n}{k} E_k E_{n-k} \\ 2(n+1) \frac{E_{n+1}}{(n+1)!} &= \sum_{k=0}^n \frac{E_k}{k!} \frac{E_{n-k}}{(n-k)!}. \end{aligned}$$

Now, observe that the coefficient of x^n in $E(x)^2$ is $F_n = \sum_{k=0}^n \frac{E_k}{k!} \frac{E_{n-k}}{(n-k)!}$. As a result,

$$\begin{aligned} 2(n+1) \frac{E_{n+1}}{(n+1)!} &= F_n \\ 2 \sum_{n \geq 1} (n+1) x^n \frac{E_{n+1}}{(n+1)!} &= \sum_{n \geq 1} x^n F_n \\ 2(E'(x) - 1) &= E(x)^2 - 1 \\ 2E'(x) &= E(x)^2 + 1 \end{aligned}$$

Solving this gives $E(x) = \sec x + \tan x$.

Problem 2.3.2. A recurrence relation of the following type is called a *three term recurrence* for a sequence p_n of polynomials with $n \geq 0$ (where each p_n is a polynomial of degree n) if there exist real numbers $(a_n), (b_n)$ such that

$$p_{n+1}(x) = (x - a_n)p_n(x) - b_n p_{n-1}(x).$$

Show that the matching polynomials of (P_n) , (C_n) , and (K_n) each satisfy a three term recurrence.

Solution

(a) Setting v as one of the “end” vertices in Lemma 1.16(b), we get

$$\text{Match}_{P_n}(x) = x \text{Match}_{P_{n-1}}(x) - \text{Match}_{P_{n-2}}(x).$$

(b) Fixing some edge e and using Lemma 1.16(c), then using the recurrence from (a), gives

$$\begin{aligned} \text{Match}_{C_n}(x) &= \text{Match}_{P_n}(x) - \text{Match}_{P_{n-2}}(x) \\ &= x \text{Match}_{P_{n-1}}(x) - \text{Match}_{P_{n-2}}(x) - x \text{Match}_{P_{n-3}}(x) + \text{Match}_{P_{n-2}}(x) \\ &= x \text{Match}_{C_{n-1}}(x) - \text{Match}_{C_{n-2}}(x). \end{aligned}$$

(c) Fixing some vertex v and using Lemma 1.16(b), we get

$$\text{Match}_{K_n}(x) = x \text{Match}_{K_{n-1}}(x) - (n-1) \text{Match}_{K_{n-2}}(x)$$

Problem 2.3.3. For $n \geq 1$, show that $\text{Match}_{C_n}(2x) = 2T_n(x)$.

Solution

The above is easily verified for $n = 1, 2$, and we saw in Problem 2.3.2 that Match_{C_n} satisfies the same recurrence as $2T_n$, which is the same as that of T_n from Proposition 1.8.

Problem 2.3.4. Let T be a tree with maximum degree d . Show that any root of $\text{Match}_T(x)$ has absolute value at most $2\sqrt{d-1}$.

Solution

By the proof of Theorem 1.18, it suffices to show that the eigenvalues of the adjacency matrix A of T are bounded from above by $2\sqrt{d-1}$.

Fix a “root” vertex r in T and denote by $d(\cdot, r)$ the distance from a vertex to r . Consider the diagonal matrix D defined by $D_{u,u} = (d-1)^{-d(u,r)/2}$. Consider $B = DAD^{-1}$. Clearly, the spectrum of A and B are equal, so it suffices to show that the eigenvalues of B are at most $2\sqrt{d-1}$. We have

$$B_{uv} = \begin{cases} (d-1)^{(d(u,r)-d(v,r))/2}, & u \leftrightarrow v, \\ 0, & \text{otherwise.} \end{cases}$$

Recall the **Perron-Frobenius Theorem**, one of whose consequences gives that the largest eigenvalue of B is at most the largest row sum of B .

Now, observe that for any vertex u with neighbour v , $d(v, r) \in \{d(u, r) - 1, d(u, r) + 1\}$. Further, because T is a tree, there can be at most one neighbour v with $d(v, r) = d(u, r) - 1$ – were there more, we would have a cycle. Therefore,

$$\lambda_{\max} \leq \max_u \sum_v B_{u,v} = \max_u \sum_{v: v \leftrightarrow u} (d-1)^{d(u,r)-d(v,r)} \leq 1 \cdot (d-1)^{1/2} + \frac{d-1}{(d-1)^{1/2}} = 2\sqrt{d-1}.$$

The idea of the above proof is similar to that of the Alon-Boppana bound, and the $2\sqrt{d-1}$ bound occurs in the definition of *Ramanujan graphs*. For more details, the interested reader may read Theorem 2.27 and following discussion in the author’s **Topics in Graph Theory notes**.

Problem 2.3.5. Show that when one runs the recurrence relation of the binomial coefficients backwards, we get signed versions of the binomial coefficients.

Solution

The usual binomial recurrence is

$$\binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1}.$$

For negative coefficients, we have

$$\binom{-(n+1)}{k} = \binom{-n}{k} - \binom{-(n+1)}{k-1}.$$

We have $\binom{0}{k} = 1$ if $k = 0$ and 0 otherwise, and also that $\binom{-n}{0} = 1$. For $n \geq 0$, let $f_n(x) = \sum_{k \geq 0} \binom{-n}{k} x^k$. Then,

$$\begin{aligned} \sum_{k \geq 1} \binom{-(n+1)}{k} x^k &= \sum_{k \geq 1} \binom{-n}{k} x^k - x \sum_{k \geq 1} \binom{-(n+1)}{k-1} x^{k-1} \\ f_{n+1}(x) - 1 &= f_n(x) - 1 - x f_{n+1}(x) \\ f_{n+1}(x) &= \frac{1}{1+x} f_n(x) \\ f_n(x) &= \frac{1}{(1+x)^n}. \end{aligned}$$

Finally,

$$\frac{1}{(1+x)^n} = \sum_{k \geq 0} (-1)^k \binom{n+k}{k} x^k,$$

so $\binom{-n}{k} = (-1)^k \binom{n+k}{k}$.

Problem 2.3.6. A restricted growth function (RGF) of length n is a sequence w_1, w_2, \dots, w_n of positive integers such that $w_1 = 1$ and $w_i \leq 1 + \max(w_1, \dots, w_{i-1})$ when $i \geq 2$. Determine the number of RGFs of length n .

Solution

Let $r_{n,k}$ be the number of RGFs w_1, \dots, w_n of length n , where $\max w_i = k$. Then,

$$r_{n,k} = r_{n-1,k-1} + k r_{n-1,k}.$$

We also have $r_{1,1} = 1$ and $r_{1,k} = 0$ for $k > 1$. Since the recurrence is identical to that of the Stirling numbers of the second kind and the base values coincide as well, $r_{n,k} = S_{n,k}$. So, the number of RGFs of length n is $\sum_k S_{n,k} = B_n$, the n th Bell number.

Problem 2.3.7. Consider a staircase board St_n with n columns where the i th column has $i - 1$ cells all stacked from the same height. We place “rooks” on this board and recall that rooks can travel on the same row or column. Two rooks can attack each other if they are on the same row or column and a placement of rooks is said to be non-attacking if no two rooks in the placement can attack each other. Determine the number of ways to place $n - k$ non-attacking rooks in St_n .

Solution

Denote by $\text{Rook}_{n,k}$ the desired quantity.

If there is no rook in the final column, we get $\text{Rook}_{n-1,k-1}$ placements, and if there is a rook, we have $\text{Rook}_{n-1,k} \cdot (n - 1 - (n - k - 1)) = k \text{Rook}_{n-1,k}$ – placing the $n - k - 1$ rooks on the rest of the board, we get k possible positions to place the final rook in the n th column. In all, we have

$$\text{Rook}_{n,k} = \text{Rook}_{n-1,k-1} + k \text{Rook}_{n-1,k}.$$

Note that this is the same as the recurrence for Stirling numbers of the second kind! Verifying that the base values are the same, we get $\text{Rook}_{n,k} = S_{n,k}$.

References

- [AH89] Kenneth Appel and Wolfgang Haken. Every planar map is four colorable. *Contemporary Mathematics*, 98, 1989.
- [BS] Matthias Beck and Raman Sanyal. *Combinatorial Reciprocity Theorems*.
- [dB55] Faa di Bruno. Note sur une nouvelle formule de calcul différentiel. *Quart. J. Math.*, (1):359–360, 1855.

- [Edm65] Jack Edmonds. Maximum matching and a polyhedron with 0,1-vertices. *Journal of Research of the National Bureau of Standards Section B Mathematics and Mathematical Physics*, page 125, 1965.
- [GG81] C. D. Godsil and I. Gutman. On the theory of the matching polynomial. *Journal of Graph Theory*, 5(2):137–144, 1981.
- [Sag20] Bruce E. Sagan. *Combinatorics: The Art of Counting*. American Mathematical Society, 2020.
- [SF99] Richard P. Stanley and Sergey Fomin. *Enumerative Combinatorics*, volume 2 of *Cambridge Studies in Advanced Mathematics*. Cambridge University Press, 1999.