

# Generating Functions

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Based on a handout by Aaron Anderson

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## Part 1: Introduction

**Definition 1:**

Say we have a sequence  $a_0, a_1, a_2, \dots$

The *generating function* of this sequence is defined as follows:

$$A(x) = \sum_{n=0}^{\infty} a_n x^n = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \dots$$

Under some circumstances, this sum does not converge, and thus  $A(x)$  is undefined.

However, we can still manipulate this infinite sum to get useful results even if  $A(x)$  diverges.

**Problem 2:**

Let  $A(x)$  be the generating function of the sequence  $a_n$ ,

and let  $B(x)$  be the generating function of the sequence  $b_n$ .

Find the sequences that correspond to the following generating functions:

- $cA(x)$
- $xA(x)$
- $A(x) + B(x)$
- $A(x)B(x)$

**Problem 3:**

Assuming  $|x| < 1$ , show that

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + \dots$$

*Hint:* use some clever algebra. What is  $x \times (1 + x + x^2 + \dots)$ ?

**Problem 4:**

Let  $A(x)$  be the generating function of the sequence  $a_n$ .

Find the sequence that corresponds to the generating function  $\frac{A(x)}{1-x}$

**Problem 5:**

Find short expressions for the generating functions for the following sequences:

- 1, 0, 1, 0, ...
- 1, 2, 4, 8, 16, ...
- 1, 2, 3, 4, 5, ...

## Part 2: Fibonacci

### Definition 6:

The *Fibonacci numbers* are defined by the following recurrence relation:

- $f_0 = 0$
- $f_1 = 1$
- $f_n = f_{n-1} + f_{n-2}$

### Problem 7:

Let  $F(x)$  be the generating function that corresponds to the Fibonacci numbers.

Find the generating function of  $0, f_0, f_1, \dots$  in terms of  $F(x)$ .

Call this  $G(x)$ .

### Problem 8:

Find the generating function of  $0, 0, f_0, f_1, \dots$  in terms of  $F(x)$ . Call this  $H(x)$ .

### Problem 9:

Calculate  $F(x) - G(x) - H(x)$  using the recurrence relation that we used to define the Fibonacci numbers.

**Problem 10:**

Using the problems on the previous page, find  $F(x)$  in terms of  $x$ .

**Definition 11:**

A *rational function*  $f$  is a function that can be written as a quotient of polynomials. That is,  $f(x) = \frac{p(x)}{q(x)}$  where  $p$  and  $q$  are polynomials.

**Problem 12:**

Solve the equation from ?? for  $F(x)$ , expressing it as a rational function.

**Definition 13:**

*Partial fraction decomposition* is an algebraic technique that works as follows:

If  $p(x)$  is a polynomial of degree 1 and  $a$  and  $b$  are constants, we can rewrite the rational function  $\frac{p(x)}{(x-a)(x-b)}$  as follows:

$$\frac{p(x)}{(x-a)(x-b)} = \frac{c}{x-a} + \frac{d}{x-b}$$

where  $c$  and  $d$  are constants.

**Problem 14:**

Now that we have a rational function for  $F(x)$ ,

find a closed-form expression for its coefficients using partial fraction decomposition.

**Problem 15:**

Using problems from the introduction and ??, find an expression for the coefficients of  $F(x)$  (and thus, for the Fibonacci numbers).

**Problem 16: Bonus**

Repeat the method of recurrence, generating function, partial fraction decomposition, and geometric series to find a closed form for the following sequence:

$$a_0 = 1; \quad a_{n+1} = 2a_n + n$$

*Hint:* When doing partial fraction decomposition with a denominator of the form  $(x - a)^2(x - b)$ , you may need to express your expression as a sum of three fractions:  $\frac{c}{(x-a)^2} + \frac{d}{x-a} + \frac{e}{x-b}$ .

## Part 3: Dice

**Definition 17:**

A *die* is a device that randomly selects a positive integer from a finite list of options. For example, the standard 6-sided die selects a value from  $[1, 2, 3, 4, 5, 6]$ . We may have many sides with the same value, as in  $[1, 1, 2, 3]$ .

To describe a die with a generating function, let  $a_k$  be the number of times  $k$  appears as a side of the die and consider  $a_0 + a_1x + a_2x^2 + \dots$

A die has a finite number of sides, so this will be a regular polynomial.

**Problem 18:**

What is the generating function of the standard 6-sided die?

**Problem 19:**

What is the generating function of the die with sides  $[1, 2, 3, 5]$ ?

**Problem 20:**

Let  $A(x)$  and  $B(x)$  be the generating functions of two dice.

What is the significance of  $A(1)$ ?

**Problem 21:**

Using formulas we found earlier, show that the  $k^{\text{th}}$  coefficient of  $A(x)B(x)$  is the number of ways to roll  $k$  as the sum of the two dice.

**Problem 22:**

Find a generating function for the sequence  $c_0, c_1, \dots$ , where  $c_k$  is the probability that the sum of the two dice is  $k$ .

**Problem 23:**

Using generating functions, find two six-sided dice whose sum has the same distribution as the sum of two standard six-sided dice.

That is, for any integer  $k$ , the number of ways that the sum of the two nonstandard dice rolls as  $k$  is equal to the number of ways the sum of two standard dice rolls as  $k$ . *Hint: factor polynomials.*

## Part 4: Coins

Consider the following problem:

“How many different ways can you make change for \$0.50 using pennies, nickels, dimes, quarters and half-dollars?”

Most ways of solving this involve awkward brute-force approaches that don't reveal anything interesting about the problem: how can we change our answer if we want to make change for \$0.51, or \$1.05, or some other quantity?

We can use generating functions to solve this problem in a general way.

**Definition 24:**

Let  $p_0, p_1, p_2, \dots$  be such that  $p_k$  is the number of ways to make change for  $k$  cents with only pennies. Similarly, let...

- $n_k$  be the number of ways to make change for  $k$  cents with only nickels;
- $d_k$  be the number of ways using only dimes;
- $q_k$  be the number of ways using only quarters;
- and  $h_k$  be the number of ways using only half-dollars.

**Problem 25:**

Let  $p(x)$  be the generating function that corresponds to  $p_n$ . Express  $p(x)$  as a rational function.

**Problem 26:**

Modify ?? to find expressions for  $n(x)$ ,  $d(x)$ ,  $q(x)$ , and  $h(x)$ .

**Definition 27:**

Now, let  $N(x)$  be the generating function for the sequence  $n_0, n_1, \dots$ , where  $n_k$  is the number of ways to make change for  $k$  cents using pennies and nickels.

Similarly, let...

- let  $D(x)$  be the generating function for the sequence using pennies, nickels, and dimes;
- let  $Q(x)$  use pennies, nickels, dimes, and quarters;
- and let  $H(x)$  use all coins.

**Problem 28:**

Express  $N(x)$  as a rational function.

**Problem 29:**

Using the previous problem, write  $D(x)$ , then  $Q(x)$ , then  $H(x)$  as rational functions.

**Problem 30:**

Using these generating functions, find recurrence relations for the sequences  $N_k, D_k, Q_k$ , and  $H_k$ .

*Hint:* Your recurrence relation for  $N_k$  should refer to the previous values of itself and some values of  $p_k$ . Your recurrence for  $D_k$  should refer to itself and  $N_k$ ; the one for  $Q_k$  should refer to itself  $D_k$ ; and the one for  $H_k$  should refer to itself and  $Q_k$ .

**Problem 31:**

Using these recurrence relations, fill following table and solve the original problem.

$n$	0	5	10	15	20	25	30	35	40	45	50
$p_k$											
$N_k$											
$D_k$											
$Q_k$											
$H_k$											

## Part 5: Extra Problems

### Problem 32: USAMO 1996 Problem 6

Determine (with proof) whether there is a subset  $X$  of the nonnegative integers with the following property: for any nonnegative integer  $n$  there is exactly one solution of  $a + 2b = n$  with  $a, b \in X$ . (The original USAMO question asked about all integers, not just nonnegative - this is harder, but still approachable with generating functions.)

### Problem 33: IMO Shortlist 1998

Let  $a_0, a_1, \dots$  be an increasing sequence of nonnegative integers such that every nonnegative integer can be expressed uniquely in the form  $a_i + 2a_j + 4a_k$ , where  $i, j, k$  are not necessarily distinct. Determine  $a_{1998}$ .

### Problem 34: USAMO 1986 Problem 5

By a partition  $\pi$  of an integer  $n \geq 1$ , we mean here a representation of  $n$  as a sum of one or more positive integers where the summands must be put in nondecreasing order. (e.g., if  $n = 4$ , then the partitions  $\pi$  are  $1 + 1 + 1 + 1$ ,  $1 + 1 + 2$ ,  $1 + 3$ ,  $2 + 2$ , and  $4$ ).

For any partition  $\pi$ , define  $A(\pi)$  to be the number of ones which appear in  $\pi$ , and define  $B(\pi)$  to be the number of distinct integers which appear in  $\pi$  (e.g., if  $n = 13$  and  $\pi$  is the partition  $1 + 1 + 2 + 2 + 2 + 5$ , then  $A(\pi) = 2$  and  $B(\pi) = 3$ ).

Show that for any fixed  $n$ , the sum of  $A(\pi)$  over all partitions of  $\pi$  of  $n$  is equal to the sum of  $B(\pi)$  over all partitions of  $\pi$  of  $n$ .

### Problem 35: USAMO 2017 Problem 2

Let  $m_1, m_2, \dots, m_n$  be a collection of  $n$  distinct positive integers. For any sequence of integers  $A = (a_1, \dots, a_n)$  and any permutation  $w = w_1, \dots, w_n$  of  $m_1, \dots, m_n$ , define an  $A$ -inversion of  $w$  to be a pair of entries  $w_i, w_j$  with  $i < j$  for which one of the following conditions holds:

- $a_i \geq w_i > w_j$
- $w_j > a_i \geq w_i$
- $w_i > w_j > a_i$

Show that for any two sequences of integers  $A = (a_1, \dots, a_n)$  and  $B = (b_1, \dots, b_n)$  and for any positive integer  $k$ , the number of permutations of  $m_1, \dots, m_n$  having exactly  $k$   $A$ -inversions is equal to the number of permutations of  $m_1, \dots, m_n$  having exactly  $k$   $B$ -inversions. (The original USAMO problem allowed the numbers  $m_1, \dots, m_n$  to not necessarily be distinct.)