Generating functions

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— *Generatingfunctionology*, H. S. Wilf

Definition: For any sequence $\{a_k\}_{k\geq 0} = a_0, a_1, a_2, a_3, \ldots$, its generating function is the formal power series

$$A(x) = a_0 + a_1x^1 + a_2x^2 + a_3x^3 + \cdots = \sum_{k\geq 0} a_k x^k.$$

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Example. Let f_k be the Fibonacci numbers starting $f_0 = 0$. Then

$$F(x) = \sum_{k\geq 0} f_kx^k = 0 + 1x^1 + 1x^2 + 2x^3 + 3x^4 + 5x^5 + 8x^6 + 13x^7 + \cdots .$$

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We will see that we can simplify this expression greatly. In fact,

$$F(x) = x\big/\big(1 - x - x^2\big).$$

We will call this the compact form of the generating function.

Why Generating Functions?

We will use generating functions to:

- Find an exact formula for the terms of a sequence.
- Prove identities involving sequences.
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Others use generating functions to:

- Use complex analysis to solve combinatorial problems.
- Understand the asymptotics of a sequence.
- Find averages and statistical properties.
- Understand **something** about a sequence.

Generating function example: Basketball

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Solution. This is a partition of 6 into parts of size at most 3, so 7:

$$3+3 \qquad 3+2+1 \qquad 3+1+1+1 \qquad 2+2+2$$
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We'll first reanalyze the question of scoring six points and then generalize to larger numbers.

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To start, break down the possible ways of getting six points total into one-point, two-point, and three-point shots.

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How many points could be scored using one-point shots?

0 pts	or	1 pt	or	2 pts	or	3 pts	or	4 pts	or	5 pts	or	6 pts
x^0	$+$	x^1	$+$	x^2	$+$	x^3	$+$	x^4	$+$	x^5	$+$	x^6

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Multiply these algebraic expressions together:

$$1 + x + 2x^2 + 3x^3 + 4x^4 + 5x^5 + 7x^6 + 7x^7 + 8x^8 + 8x^9 + \\ 8x^{10} + 7x^{11} + 7x^{12} + 5x^{13} + 4x^{14} + 3x^{15} + 2x^{16} + x^{17} + x^{18}$$

and find the coefficient of the x^6 term.

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Why does this work? A score a from 1-pt, b from 2-pt, c from 3-pt, gives a term in the product of $x^a x^b x^c = x^{a+b+c}$. Collecting like terms makes the coefficient of x^k the number of ways to score k points. (x^{15}?)

Generating function example: Basketball

In order to take into account all the ways to score 98 points, we include more terms in each factor:

One-point shots: $1 + x + x^2 + \cdots +$ $= \underline{\hspace{3cm}}.$

Two-point shots: $1 + x^2 + x^4 + \cdots +$ $= \underline{\hspace{3cm}}.$

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Conclusion: The generating function for the number of ways to score any number of points in basketball is

$$b(x) = \frac{1}{(1-x)(1-x^2)(1-x^3)}.$$

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Notation: $[x^k]f(x)$ is the coefficient of x^k in the expansion of the generating function $f(x)$. Example. $[x^{98}]b(x) = 850$.

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- The number of apples is even.
- The number of bananas is a multiple of five.
- The number of oranges is at most four.
- The number of pears is zero or one.

Strategy. Write down a power series for each piece of fruit, multiply them together, and extract the coefficient of x^k.

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$$D(x)^2 = x^2(1+x)^2\left(1-x+x^2\right)^2\left(1+x+x^2\right)^2.$$

$$= \left[x(1+x)\left(1+x+x^2\right)\right] \cdot \left[x\left(1-x+x^2\right)^2(1+x)\left(1+x+x^2\right)\right]$$

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$$

Die F: $\{1, 2, 2, 3, 3, 4\}$ and die G: $\{1, 3, 4, 5, 6, 8\}$

Key series

⋆ Use these key series to collapse sums to compact forms or extract coefficients. ⋆

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Manipulations on $A(x) = \sum_{k \geq 0} a_k x^k$

Example. Find the coefficient of x^9 in $\frac{1}{(1-4x)^{12}}$.

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Question: Suppose we can factor out a power of x from $A(x)$. Let $A(x) = x^b B(x)$. How can we simplify $[x^k]\big(A(x)\big)$?

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Answer:

Memories of calculus. . .

With formal power series, we interchange derivatives, integrals, sums.

$$\sum_{k\geq 0} \frac{d}{dx} x^k = \frac{d}{dx} \sum_{k\geq 0} x^k$$

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Memories of calculus. . .

With formal power series, we interchange derivatives, integrals, sums.

$$\sum_{k\geq 0} kx^{k-1} = \sum_{k\geq 0} \frac{d}{dx} x^k = \frac{d}{dx} \sum_{k\geq 0} x^k = \frac{d}{dx} \frac{1}{1-x} = \frac{1}{(1-x)^2}$$

$$\sum_{k\geq 0} \frac{x^{k+1}}{k+1} = \sum_{k\geq 0} \int_0^x x^k \, dx = \int_0^x \sum_{k\geq 0} x^k \, dx = \int_0^x \frac{1}{1-x} \, dx = -\ln|1-x|$$

How these manipulations interact with $A(x) = \sum_{k\geq 0} a_k x^k$:

$$\sum_{k\geq 0} k a_k x^k = \qquad \sum_{k\geq 0} p(k) a_k x^k = p\left(x \frac{d}{dx}\right)(A(x))$$

Example. Find $\sum_{k\geq 0} \frac{k^2+4k+5}{k!}$