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On the Central Antecedents of Integer (and Other) Sequences

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Abstract

With each power series $g(x)$ with $g(0) \neq 0$, we associate a power series $G(x)$ such that $[x^n]G(x)^n = [x^n]g(x)$. We give examples for well-known integer sequences, including the Catalan numbers and generalized Catalan numbers, and explore the antecedents of rational sequences, including the Bernoulli numbers and the harmonic numbers.

1 Introduction

The central coefficients of common number triangles have been objects of study over the history of mathematics. The best known such sequence is the sequence $\binom{2n}{n}$ A000984, the central coefficient sequence of Pascal's triangle. It has many important properties. Germane to this note is the following property. We have

$$\binom{2n}{n} = [x^n]\frac{1}{\sqrt{1-4x}} = [x^n](1+2x+x^2)^n.$$

We say that the sequence $1, 2, 1, 0, 0, 0, \ldots$ is a *central antecedent* of the sequence $\binom{2n}{n}$. In a similar way, the sequence $1, 1, 1, 0, 0, 0, \ldots$ is the central antecedent of the central trinomial numbers t_n A002426 that begin $1, 1, 3, 7, 19, 51, 141, 393, 1107, \ldots$. In this case, we have

$$[x^n]\frac{1}{\sqrt{1-2x-3x^2}} = [x^n](1+x+x^2)^n.$$

By analogy, we say that $(1+x)^2 = 1+2x+x^2$ is the central antecedent of $\frac{1}{\sqrt{1-4x}}$, and that $1+x+x^2$ is the central antecedent of $\frac{1}{\sqrt{1-2x-3x^2}}$.

In general, if two generating functions are related by $[x^n]g(x) = [x^n]G(x)^n$, we shall say that $G(x)$ is a *central antecedent* of $g(x)$. If under these circumstances we have $b_n = [x^n]G(x)$, we shall say that the sequence b_n is a *central antecedent sequence* of the sequence $a_n = [x^n]g(x)$.

In the sequel, we shall identify integer sequences by their sequence number in the *On-Line Encyclopedia of Integer Sequences* [12, 13].

Another perspective on the above is given by the following diagonalization formula [9]. Given two power series

$$g(x) = g_0 + g_1 x + g_2 x^2 + \dots,$$

and

$$f(x) = f_0 + f_1 x + f_2 x^2 + \dots,$$

we have

$$[x^n]g(x)f(x)^n = [x^n]\left[\frac{g(w)}{1-xf'(w)}|w = xf(w)\right].$$

The terms $[x^n]g(x)f(x)^n$ then correspond to the diagonal terms of the matrix whose (n,k)-term is given by

$$[x^n]g(x)f(x)^k.$$

We now note that

$$[x^n]g(x)f(x)^n = [x^{2n}]g(x)(xf(x))^n,$$

thus expressing the terms $[x^n]g(x)f(x)^n$ as the "central" terms of the lower-triangular matrix with (n,k)-term $[x^n]g(x)(xf(x))^k$. We have opted to use the term "central" in this context, although, as pointed out by a reviewer, the term "diagonal" could have been used with equal justification.

We note that in the diagonalization formula above, we have the condition $w = xf(w)$ which defines the power series $w(x)$. In fact, we have

$$w = xf(w) \Longrightarrow \frac{w}{f(w)} = x \Longrightarrow w(x) = \operatorname{Rev}\left(\frac{x}{f}\right)(x),$$

where $\operatorname{Rev} F(x)$ denotes the compositional inverse of $F(x)$, often denoted by $\bar{F}(x)$ or $F^{\langle -1\rangle}(x)$. Thus we have

$$[x^n]g(x)f(x)^n = [x^n]\frac{g(\operatorname{Rev}\left(\frac{x}{f}\right))}{1-xf'\left(\operatorname{Rev}\left(\frac{x}{f}\right)\right)}.$$

Example 1. We let $g(x)=\frac{1}{\sqrt{1-4x}}$, and $f(x)=\frac{1}{1-x}$. The matrix with (n,k)-term $[x^n]g(x)f(x)^k$ begins

$$\left(\begin{array}{ccccccc} \mathbf{1} & 1 & 1 & 1 & 1 & 1 & 1 \\ 2 & \mathbf{5} & 8 & 11 & 14 & 17 & 20 \\ 6 & 21 & \mathbf{45} & 78 & 120 & 171 & 231 \\ 20 & 83 & 218 & \mathbf{452} & 812 & 1325 & 2018 \\ 70 & 319 & 973 & 2329 & \mathbf{4765} & 8740 & 14794 \\ 252 & 1209 & 4128 & 11115 & 25410 & \mathbf{51630} & 96012 \\ 924 & 4551 & 16935 & 50280 & 126510 & 281400 & \mathbf{569436} \end{array}\right),$$

while the lower-triangular matrix with (n,k)-term $[x^n]g(x)(xf(x))^k$ begins

$$\left(\begin{array}{ccccccc} \mathbf{1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 1 & 0 & 0 & 0 & 0 & 0 \\ 6 & \mathbf{5} & 1 & 0 & 0 & 0 & 0 \\ 20 & 21 & 8 & 1 & 0 & 0 & 0 \\ 70 & 83 & \mathbf{45} & 11 & 1 & 0 & 0 \\ 252 & 319 & 218 & 78 & 14 & 1 & 0 \\ 924 & 1209 & 973 & \mathbf{452} & 120 & 17 & 1 \end{array}\right).$$

We have $f'(x)=\frac{3}{(1-3x)^2}$ and $\text{Rev}\left(\frac{x}{f(x)}\right)=\frac{1-\sqrt{1-12x}}{6}$. Then we find that

$$[x^n]g(x)f(x)^n=[x^{2n}]g(x)(xf(x))^n=[x^n]\frac{\sqrt{3}(1-12x+\sqrt{1-12x})}{2(1-12x)\sqrt{1+2\sqrt{1-12x}}}.$$

We infer that the sequence that begins $1,5,45,452,4765,51630,\ldots$ has generating function

$$\frac{\sqrt{3}(1-12x+\sqrt{1-12x})}{2(1-12x)\sqrt{1+2\sqrt{1-12x}}}.$$

Historically, the coefficients $\binom{2n}{n}$ are called the central binomial coefficients because they appear as the central numbers of Pascal's triangle when this is displayed as a pyramid.

$$\begin{array}{ccccccccccccc} &&&&&& \boxed{1} &&&&&& \\ &&&&& 1 && 1 &&&&& \\ &&&& 1 && \boxed{2} && 1 &&&& \\ &&& 1 && 3 && 3 && 1 &&& \\ && 1 && 4 && \boxed{6} && 4 && 1 && \\ & 1 && 5 && 10 && 10 && 5 && 1 & \\ 1 && 6 && 15 && \boxed{20} && 15 && 6 && 1 \end{array}$$

2 An example from Henrici

Henrici [6] gives the example of the use of Lagrange inversion to derive $g(x)$ from $G(x)$ in the case of the trinomial numbers $t_n = [x^n](1+x+x^2)^n$. The version of Lagrange inversion used for this takes the following form.

Proposition 2. *[6, Corollary 1.9c p. 59] For $S \in \mathbb{K}[[x]]$ and $P \in x\mathbb{K}[[x]]$, with $Q = P^{\langle -1 \rangle}$, we have*

$$(S \circ Q)Q' = \sum_{n=0}^{n} \operatorname{res}(SP^{-n-1})x^n.$$

Here, the coefficient a_1 of x^{-1} in a Laurent series $L = \sum_{k=0}^{\infty} a_k x^k$ is called the *residue* of L, denoted by $\operatorname{res}(L)$. The notation $Q = P^{\langle -1 \rangle}$ means that Q is the compositional inverse of P. The field $\mathbf{K}$ is assumed to be of characteristic zero. We then have

$$[x^n](1+x+x^2)^n = \operatorname{res}[x^{-n-1}(1+x+x^2)^n] = \operatorname{res}(SP^{-n-1}),$$

where

$$S(x) = \frac{1}{1+x+x^2}, \quad \text{and} \quad P(x) = \frac{x}{1+x+x^2}.$$

From this we infer that

$$\frac{1+Q+Q^2}{Q} = x,$$

which we may solve for Q to get

$$Q = \frac{2x}{1-x+\sqrt{1-2x-3x^2}}.$$

Then

$$(S \circ Q)(x) = S(Q(x)) = \frac{1}{1+Q+Q^2} = \frac{x}{Q} = \frac{1-x+\sqrt{1-2x-3x^2}}{2}.$$

Thus we have

$$(S \circ Q)Q' = \frac{1-x+\sqrt{1-2x-3x^2}}{2} \cdot \frac{1-x-\sqrt{1-2x-3x^2}}{2x^2\sqrt{1-2x-3x^2}} = \frac{1}{\sqrt{1-2x-3x^2}}.$$

This then gives an example of going from $G(x)$ to $g(x)$. In this note, the emphasis will be on going in the other direction.

3 The main results

We shall use the techniques of Lagrange inversion [8] and the method of coefficients [9]. We need the following version of Lagrange inversion in the sequel [7, 8, 14]. We use the notation $\operatorname{Rev}(P) = P^{\langle -1 \rangle}$, the compositional inverse of P.

Theorem 3. *(Lagrange-Bürmann inversion). Suppose that a formal power series $w = w(t)$ is implicitly defined by the relation $w = t\phi(w)$, where $\phi(t)$ is a formal power series such that $\phi(0) \neq 0$. Then, for any formal power series $F(t)$,*

$$[t^n]F(w(t)) = \frac{1}{n}[t^{n-1}]F'(t)(\phi(t))^n.$$

A consequence of this is that if $v(x) = \sum_{n\geq 0} v_n x^n$ is a power series with $v_0 = 0$, $v_1 \neq 0$, we have

$$[x^n]F(\mathrm{Rev}(v)) = \frac{1}{n}[x^{n-1}]F'(x)\left(\frac{x}{v}\right)^n.$$

Proposition 4. *We have*

$$[x^n]\left(1 + x\frac{d}{dx}\ln\left(\frac{1}{x}\mathrm{Rev}(f(x))\right)\right) = [x^n]\left(\frac{x}{f(x)}\right)^n.$$

Proof. We have

$$\begin{aligned}
[x^n]\left(1 + x\frac{d}{dx}\ln\left(\frac{1}{x}\mathrm{Rev}(f(x))\right)\right) &= 0 + [x^{n-1}]\frac{d}{dx}\ln\left(\frac{1}{x}\mathrm{Rev}(f(x))\right)\\
&= n[x^n]\ln\left(\frac{1}{x}\mathrm{Rev}(f(x))\right)\\
&= n[x^n]\left(\ln\left(\mathrm{Rev}(f(x))\right) - \ln(x)\right)\\
&= n\cdot\frac{1}{n}[x^{n-1}]\frac{1}{x}\left(\frac{x}{f(x)}\right)^n - \frac{n}{n}[x^{n-1}]\frac{1}{x}(1)^n\\
&= [x^n]\left(\frac{x}{f(x)}\right)^n - [x^n].1\\
&= [x^n]\left(\frac{x}{f(x)}\right)^n.
\end{aligned}$$

□

Corollary 5. *If $[x^n]g(x) = [x^n]G(x)^n$, then we have*

$$g(x) = 1 + x\frac{d}{dx}\ln\left(\frac{1}{x}\mathrm{Rev}\left(\frac{x}{G(x)}\right)\right).$$

Theorem 6. *Let $g(x)$ be a power series with $g(0) \neq 0$. Then the central antecedent $G(x)$ of $g(x)$, which satisfies $[x^n]G(x)^n = [x^n]g(x)$, is given by*

$$G(x) = \frac{x}{\mathrm{Rev}\left(xe^{\int_0^x \frac{g(t)-1}{t}\,dt}\right)}.$$

Example 7. We take the example of $\binom{2n}{n} = [x^n]\frac{1}{\sqrt{1-4x}}$. We have the following steps.

1. Set $g(x) = \frac{1}{\sqrt{1-4x}}$.
2. Form $\frac{g(x)-1}{x} = \frac{1-\sqrt{1-4x}}{x\sqrt{1-4x}}$.
3. Carry out the integration $\int_0^x \frac{g(t)-1}{t}\,dt = -2\ln\left(\frac{1+\sqrt{1-4x}}{2}\right)$.
4. Calculate $xe^{-2\ln\left(\frac{1+\sqrt{1-4x}}{2}\right)} = \frac{1-2x-\sqrt{1-4x}}{2x} = c(x) - 1$.
5. Revert $\frac{1-2x-\sqrt{1-4x}}{2x}$ to get $\frac{x}{(1+x)^2}$.
6. Calculate $G(x) = \frac{x}{\frac{x}{(1+x)^2}} = (1+x)^2$.

In this list, we have used

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

which is the generating function of the Catalan numbers $C_n = \frac{1}{n+1}\binom{2n}{n}$ A000108. It is instructive to visualize the sequences encountered in this list of operations. Thus we have

1. $1, 2, 6, 20, 70, 252, 924, 3432, \ldots$.
2. $2, 6, 20, 70, 252, 924, 3432, \ldots$.
3. $0, 2, 3, \frac{20}{3}, \frac{35}{2}, \frac{252}{5}, 154, \ldots$.
4. $1, 2, 5, 14, 42, 132, 429, \ldots$.
5. $0, 1, -2, 3, -4, 5, -6, 7, \ldots$.
6. $1, 2, 1, 0, 0, 0, \ldots$.

We conclude that

$$\binom{2n}{n} = [x^n]\frac{1}{\sqrt{1-4x}} = [x^n](1+x)^{2n}.$$

Example 8. We now take the example of $g(x) = \frac{1}{\sqrt{1-2x-3x^2}}$, the generating function of the central trinomial coefficients t_n [10]. We have the following list of operations.

1. Set $g(x) = \frac{1}{\sqrt{1-2x-3x^2}}$.
2. Form $\frac{g(x)-1}{x} = \frac{1-\sqrt{1-2x-3x^2}}{x\sqrt{1-2x-3x^2}}$.
3. Carry out the integration $\int_0^x \frac{g(t)-1}{t}\,dt = \ln\left(\frac{-1+x+\sqrt{1-2x-3x^2}}{2}\right) - 2\ln(x) - \pi i\,\mathrm{sgn}(x)$.
4. Calculate $xe^{\ln\left(\frac{-1+x+\sqrt{1-2x-3x^2}}{2}\right)-2\ln(x)-\pi i\,\mathrm{sgn}(x)} = \frac{1-x-\sqrt{1-2x-3x^2}}{2x} = xm(x)$.

5. Revert $xm(x)$ to get $\frac{x}{1+x+x^2}$.

6. Calculate $G(x) = \frac{x}{\frac{x}{1+x+x^2}} = 1 + x + x^2$.

In this list, we have

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

This is the generating function of the Motzkin numbers $M_n = \sum_{k=0}^{\lfloor \frac{n}{2} \rfloor} \binom{n}{2k} C_k$.

We conclude that

$$t_n = [x^n] \frac{1}{\sqrt{1 - 2x - 3x^2}} = [x^n](1 + x + x^2)^n.$$

4 The central antecedent of $1, r, r, r, \ldots$

In this section, we shall explore the antecedent of the sequence

$$1, r, r, r, \ldots$$

with generating function $1 + rx/(1 - x)$.

Proposition 9. *The central antecedent of the sequence* $1, r, r, r, \ldots$ *has generating function*

$$\frac{1}{\sum_{n=0}^{\infty} \frac{(-1)^n \binom{(n+1)r}{n} x^n}{n+1}}.$$

Proof. Let $g(x) = 1 + \frac{rx}{1-x}$. Then

$$\frac{g(x) - 1}{x} = \frac{r}{1 - x}.$$

We have

$$\int_0^x \frac{r}{1 - t}\, dt = -r \ln(x - 1) + \pi i r.$$

Then

$$e^{\int_0^x \frac{r}{1-t}\, dt} = \frac{1}{(1 - x)^r}.$$

The reversion of $\frac{x}{(1-x)^r}$ is now given by $x \sum_{n=0}^{\infty} \frac{(-1)^n \binom{(n+1)r}{n} x^n}{n+1}$. The statement of the proposition now results from this. $\square$

5 The antecedent of $\frac{1+(a-b)x}{(1+ax)^2}$

We let
$$g(x)=\frac{1+(a-b)x}{(1+ax)^2}.$$
In order to find the central antecedent of $g(x)$, we have the following list of operations.

1. Set $g(x)=\frac{1+(a-b)x}{(1+ax)^2}$.
2. Form $\frac{g(x)-1}{x}=-\frac{a+b+a^2x}{(1+ax)^2}$.
3. Carry out the integration $\int_0^x \frac{g(t)-1}{t}\,dt=-\ln(1+ax)-\frac{bx}{1+ax}$.
4. Calculate $xe^{-\ln(1+ax)-\frac{bx}{1+ax}}=\frac{xe^{\frac{bx}{1+ax}}}{1+ax}$.
5. Revert $\frac{xe^{\frac{bx}{1+ax}}}{1+ax}$ to get $\frac{-xW(-x)}{-axW(-x)-bx}$.
6. Calculate $G(x)=\frac{x}{\frac{-xW(-x)}{-axW(-x)-bx}}=-ax-\frac{bx}{W(-x)}$.

Here, $W(x)$ is the Lambert function [2], given by the reversion of xe^x (we use the principal branch W_0). We then have the following proposition.

Proposition 10. *We have*
$$[x^n]\frac{1+(a-b)x}{(1+ax)^2}=[x^n]\left(-ax-\frac{bx}{W(-x)}\right)^n.$$

Example 11. When $a=b=-1$, we have $g(x)=\frac{1}{(1-x)^2}$, the generating function of the counting numbers $1,2,3,\ldots$ A000027. Thus we have
$$n+1=[x^n]\frac{1}{(1-x)^2}=[x^n]\left(x+\frac{x}{W(-x)}\right)^n.$$
More generally, we have
$$rn+1=[x^n]\frac{1+(r-1)x}{(1-x)^2}=[x^n]\left(x+\frac{rx}{W(-x)}\right)^n.$$

6 The case $G(x)=1+ax+bx^2$

Proposition 12. *We have*

$$[x^n](1+ax+bx^2)^n = [x^n]\frac{1}{\sqrt{1-2ax+(a^2-4b)x^2}}.$$

Proof. We let $G(x)=1+ax+bx^2$. Then

$$\frac{1}{x}\operatorname{Rev}\frac{x}{G(x)} = \frac{1-ax-\sqrt{1-2ax+(a^2-4b)x^2}}{2bx^2}.$$

It follows that

$$g(x) = 1 + x\frac{d}{dx}\ln\left(\frac{1}{x}\operatorname{Rev}\left(\frac{x}{G(x)}\right)\right) = \frac{1}{\sqrt{1-2ax+(a^2-4b)x^2}}.$$

$\square$

The sequences $u_n = [x^n](1+ax+bx^2)^n = [x^n]\frac{1}{\sqrt{1-2ax+(a^2-4b)x^2}}$ are well documented in the literature, as they have many interesting properties [10]. For instance,

1. They have exponential generating function $I_0(2\sqrt{b}x)e^{ax}$
2. They are moment sequences with $u_n = \frac{1}{\pi}\int_{a-2\sqrt{b}}^{a+2\sqrt{b}} \frac{x^n}{\sqrt{-x^2+2ax-a^2+4b}}\,dx$
3. The generating function $g(x)$ has the following continued fraction expression

$$g(x) = \cfrac{1}{1-ax-\cfrac{2bx^2}{1-ax-\cfrac{bx^2}{1-ax-\cfrac{bx^2}{1-ax-\cdots}}}}.$$

7 The Catalan numbers

We have the following result concerning the central antecedent for the Catalan numbers.

Proposition 13. *We have*

$$C_n = [x^n]\left(2x - xW(-x) - \frac{x}{W(-x)}\right)^n.$$

Proof. We proceed with the following steps.

1. Set $g(x) = c(x) = \frac{1-\sqrt{1-4x}}{2x}$.
2. Form $\frac{g(x)-1}{x} = \frac{c(x)-1}{x} = c(x)^2$.
3. Carry out the integration $\int_0^x c(t)^2\,dt = -2\ln\left(\frac{1+\sqrt{1-4x}}{2}\right) + \frac{\sqrt{1-4x}+2x-1}{2x}$.
4. Calculate $\exp\left(-2\ln\left(\frac{1+\sqrt{1-4x}}{2}\right) + \frac{\sqrt{1-4x}+2x-1}{2x}\right) = e^{-\frac{1-2x-\sqrt{1-4x}}{2x}}\frac{1-2x-\sqrt{1-4x}}{2x}$.
5. Revert $xe^{-\frac{1-2x-\sqrt{1-4x}}{2x}}\frac{1-2x-\sqrt{1-4x}}{2x}$ to get $\frac{x}{G(x)}$.

$\square$

We can also write this result as

$$C_n = [x^n]\left(\frac{-x(1-W(-x))^2}{W(-x)}\right)^n.$$

We have

$$C_n = [x^n]\left(1 + x + \frac{x^2}{2} + \frac{x^3}{3} + \frac{3x^4}{8} + \frac{8x^5}{15} + \frac{125x^6}{144} + \cdots\right)^n.$$

We note that we have

$$\binom{2n+1}{n+1} = [x^n]\left(\frac{x(1+W(-x))^2}{W(-x)}\right)^n.$$

Compare this with

$$n+1 = [x^n]\left(\frac{x(1+W(-x))}{W(-x)}\right)^n,$$

while

$$1-n = [x^n]\left(\frac{x(1-W(-x))}{W(-x)}\right)^n.$$

It is possible to generalize this result in two directions. The first is to replace the specific quadratic $(1-W(-x))^2$ by the more general quadratic $1-aW(-x)-bW(-x)^2$. We find that the terms

$$[x^n]\left(\frac{-x(1-aW(-x)-bW(-x)^2)}{W(-x)}\right)^n,$$

which begin

$$1, a-1, a^2-2a-2b, a^3-3a^2-6ab+3b, a^4-4a^3-12a^2b+12ab+6b^2, \ldots,$$

can be represented by

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ -2b & -2 & 1 & 0 & 0 & 0 \\ 3b & -6b & -3 & 1 & 0 & 0 \\ 6b^2 & 12b & -12b & -4 & 1 & 0 \\ -10b^2 & 30b^2 & 30b & -20b & -5 & 1 \\ & & \vdots & & & \end{pmatrix} \begin{pmatrix} 1 \\ a \\ a^2 \\ a^3 \\ a^4 \\ a^5 \\ \vdots \end{pmatrix}.$$

The matrix is the exponential Riordan array [1] $[I_0(2i\sqrt{b}x) - \frac{I_1(2i\sqrt{b}x)}{i\sqrt{b}}, x]$ and so we have

$$[x^n]\left(\frac{-x(1-aW(-x)-bW(-x)^2)}{W(-x)}\right)^n = n![x^n]\left(I_0(2i\sqrt{b}x) - \frac{I_1(2i\sqrt{b}x)}{i\sqrt{b}}\right)e^{ax},$$

or equivalently

$$[x^n]\left(\frac{-x(1-aW(-x)-bW(-x)^2)}{W(-x)}\right)^n = [x^n]\frac{1-(a-2b)x-\sqrt{1-2ax+(a^2+4b)x^2}}{2bx\sqrt{1-2ax+(a^2+4b)x^2}}.$$

The general term of the sequence $1, a-1, a^2-2a-2b, a^3-3a^2-6ab+3b, \ldots$ is given by

$$\sum_{k=0}^{n} \binom{n}{k}\binom{n-k}{\lfloor\frac{n-k}{2}\rfloor} b^{\lfloor\frac{n-k}{2}\rfloor}(-1)^{\binom{n-k+1}{2}} a^k.$$

For instance, the Motzkin sums A005043 that begin

$$1, 0, 1, 1, 3, 6, 15, 36, 91, 232, 603, 1585, 4213, \ldots,$$

are given by $a=1, b=-1$ and hence the terms of this sequence are given by

$$[x^n]\left(\frac{-x(1-W(-x)+W(-x)^2)}{W(-x)}\right)^n.$$

Similarly the binomial transform of the Catalan numbers A007317, which begins

$$1, 2, 5, 15, 51, 188, 731, 2950, 12235, \ldots,$$

has its general term given by

$$[x^n]\left(\frac{-x(1-3W(-x)+W(-x)^2)}{W(-x)}\right)^n.$$

The other direction for generalization is to modify $(1-W(-x))^2$ to $(1-W(-x))^m$. We then have the following conjecture.

Conjecture 14. We have

$$[x^n]g_m(x) = [x^n]\left(\frac{-x(1-W(-x))^m}{W(-x)}\right)^n,$$

where $g_m(x)$ is the generating function of the central coefficients $\frac{(m-2)n+1}{(m-1)n+1}\binom{mn}{n}$ of the Riordan array $(c(x), xc(x)^{m-2})$.

For $m = 0, \ldots, 5$ we get the sequences

1	−1	0	0	0	0	0	0	0	0	0
1	0	−1	−2	−3	−4	−5	−6	−7	−8	−9
1	1	2	5	14	42	132	429	1430	4862	16796
1	2	9	48	275	1638	9996	62016	389367	2466750	15737865
1	3	20	154	1260	10659	92092	807300	7152444	63882940	574221648
1	4	35	350	3705	40480	451269	5101360	58261125	670609940	7766844470

The sequence $\frac{(m-2)n+1}{(m-1)n+1}\binom{mn}{n}$ counts standard Young tableaux of shape $[(m-1)n, n]$. Note that we also have

$$[x^n]g_m(x) = [x^n]c(x)^{(m-2)n+1}.$$

The number array above is essentially A214776.

8 Divisors and partitions

We define the sequence σ_n^* as follows.

$$\sigma_n^* = 0^n + \sum_{d=0}^{n}[d|n]d.$$

Here, we have used the Iverson notation [5] $[\mathcal{P}] = 1$ if the statement $\mathcal{P}$ is true, otherwise the value is 0. The sequence σ_n^* (essentially A000203) begins

$$1, 1, 3, 4, 7, 6, 12, 8, 15, 13, 18, \ldots.$$

Setting $g(x) = \sum_{n=0}^{\infty}\sigma_n^* x^n$, we have

$$g(x) = 1 - \frac{x\frac{d}{dx}\prod_{k=1}^{\infty}(1-x^k)}{\prod_{k=1}^{\infty}(1-x^k)}.$$

Thus we have

$$\frac{g(x)-1}{x} = \frac{\frac{d}{dx}\prod_{k=1}^{\infty}(1-x^k)}{\prod_{k=1}^{\infty}(1-x^k)}.$$

We then have

$$e^{\int_0^x \frac{g(t)-1}{t}\,dt} = \pi(x) = \prod_{k=1}^{\infty} \frac{1}{1-x^k}.$$

This is the generating function of the partition numbers $\pi(x) = \sum_{n=0}^{\infty} p_n x^n$ A000041. Thus we have the following proposition.

Proposition 15. *Let*

$$\sigma_n^* = 0^n + \sum_{d=0}^{n} [d|n] d,$$

and let $\pi(x) = \sum_{n=0}^{\infty} p_n x^n$ *where* p_n *are the partition numbers. Then we have*

$$\sigma_n^* = [x^n] \left(1 - \frac{x \frac{d}{dx} \prod_{k=1}^{\infty}(1-x^k)}{\prod_{k=1}^{\infty}(1-x^k)}\right) = [x^n] \left(\frac{x}{\operatorname{Rev}(x\pi(x))}\right)^n.$$

Numerically, we have

$$\sigma_n^* = [x^n](1 - x + 2x^3 - 3x^4 + 5x^6 - 21x^8 + 14x^9 + 117x^{10} + \cdots)^n.$$

The central antecedent sequence of the partition numbers begins

$$1, 1, \frac{1}{2}, -\frac{1}{3}, \frac{1}{8}, -\frac{2}{15}, \frac{71}{144}, -\frac{11}{10}, \frac{9583}{5760}, \ldots.$$

9 The J. C. P. Miller recurrence

The J. C. P. Miller recurrence [6, 3, 15] gives a method to calculate the coefficients of the power series $f(x)^n$ knowing the coefficients of $f(x)$. Thus assume that

$$f(x)^n = \sum_{k=0}^{Nn} c_k x^k$$

where $f(x) = \sum_{k=0}^{N} a_k x^k$, where N could be ∞ and $a_0 \neq 0$, then we have

$$c_0 = a_0^n, \quad c_k = \frac{1}{ka_0} \sum_{j=1}^{N} ((n+1)j - k) a_j c_{n-j}.$$

We reproduce the proof by Zeilberger [3, 15]. The term c_k is the coefficient of x^0 in the Laurent series expansion of $\frac{f(x)^n}{x^k}$. For any Laurent series $g(x)$, the coefficient of x^0 in $x\frac{d}{dx}g(x)$ is zero. Thus

$$\begin{aligned}
0 &= [x^0] x \frac{d}{dx} \frac{f(x)^{n+1}}{x^k} \\
&= [x^0] \left((-k(a_0 + a_1 x + \cdots + a_N x^N) \frac{f(x)^n}{x^k} + (n+1)(a_1 + 2a_2 x + \cdots + N a_N x^{N-1}) \frac{f(x)^n}{x^{k-1}} \right) \\
&= [x^0] \left(-k \left(a_0 \frac{f(x)^n}{x^k} + a_1 \frac{f(x)^n}{x^{k-1}} + \cdots + a_N \frac{f(x)^n}{x^{k-N}} \right) + (n+1) \left(a_1 \frac{f(x)^n}{x^{k-1}} + 2a_2 \frac{f(x)^n}{x^{k-2}} + \cdots + N a_N \frac{f(x)^n}{x^{k-N}} \right) \right) \\
&= -k(a_0 c_k + a_1 c_{k-1} + \cdots + a_N c_{k-N}) + (n+1)(a_1 c_{k-1} + 2a_2 c_{k-2} + \cdots + N a_N c_{k-N}).
\end{aligned}$$

The recurrence follows from this.

We can use this recurrence to iteratively calculate the elements $[x^n]G(x)^n$.

Example 16. We let $G(x)=\sum_{n=0}^{\infty} C_n x^n$ be the generating function of the Catalan numbers. We wish to calculate $[x^n]G(x)^n$. To this end, we let

$$c(n,k)=\begin{cases}1, & \text{if } n=0;\\ \frac{1}{n}\sum_{j=1}^{n}(kj-j-n)C_j c(n-j,k), & \text{otherwise.}\end{cases}$$

Then $[x^n]G(x)^n$ is given by $c(n,n)$. In this case, we obtain the sequence $\binom{3n-1}{2n}$ which begins

$$1,1,5,28,165,1001,6188,38760,245157,1562275\ldots.$$

This is essentially A025174. The numbers $c(n,n)$ are the central coefficients of the Riordan array $(1,xc(x))$.

$$\left(\begin{array}{ccccccccc}
\mathbf{1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \mathbf{1} & 1 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 2 & 2 & 1 & 0 & 0 & 0 & 0 & 0\\
0 & 5 & \mathbf{5} & 3 & 1 & 0 & 0 & 0 & 0\\
0 & 14 & 14 & 9 & 4 & 1 & 0 & 0 & 0\\
0 & 42 & 42 & \mathbf{28} & 14 & 5 & 1 & 0 & 0\\
0 & 132 & 132 & 90 & 48 & 20 & 6 & 1 & 0\\
0 & 429 & 429 & 297 & \mathbf{165} & 75 & 27 & 7 & 1
\end{array}\right).$$

10 Some numerical results

Example 17. The Bernoulli numbers B_n can be defined by

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

They begin

$$1,-\frac{1}{2},\frac{1}{6},0,-\frac{1}{30},0,\frac{1}{42},0,-\frac{1}{30},0,\ldots.$$

Letting $g(x)=\sum_{k=0}^{n} B_k x^k$ and proceeding as above will allow us to find the first $n+1$ terms of the central antecedent of the Bernoulli numbers. We can proceed as follows. For a given $n\ge 0$, we

1. Set $g(x)=\sum_{k=0}^{n} B_k x^k$.

2. Form $\frac{g(x)-1}{x}=\sum_{k=1}^{n} B_k x^k$.

3. Carry out the integration $\int_0^x \frac{g(t)-1}{t}\,dt = \sum_{k=1}^n B_k \frac{x^{k+1}}{k}$.

4. Evaluate $xe^{\sum_{k=1}^n B_k \frac{x^{k+1}}{k}}$ and revert.

For fixed n, we can carry out this reversion as follows. We form the Riordan array $(1, f(x))$ [11] where $f(x)$ is the n-degree polynomial that approximates $xe^{\sum_{k=1}^n B_k \frac{x^{k+1}}{k}}$. We invert this Riordan array and it follows that the elements of the second $(k = 1)$ column of the inverse matrix are the Taylor series coefficients of the n-degree polynomial that approximates the reversion sought. Shifting this once (division by x) and taking the reciprocal then gives us the first n Taylor series coefficients of the antecedent power series, or equivalently, the first n terms of the central antecedent sequence of the Bernoulli numbers.

We find in this manner that the central antecedent sequence of the Bernoulli numbers begins

$$1, -\frac{1}{2}, -\frac{1}{24}, 0, \frac{3}{640}, 0, -\frac{1525}{580608}, 0, \frac{615881}{199065600}, 0, \ldots.$$

Example 18. The harmonic numbers $\sum_{k=1}^n \frac{1}{k}$ for $k = 1, 2, \ldots$ begin

$$1, \frac{3}{2}, \frac{11}{6}, \frac{25}{12}, \frac{137}{60}, \frac{49}{20}, \frac{363}{140}, \frac{761}{280}, \ldots.$$

Proceeding as before, we find that the central antecedent sequence of the harmonic numbers begins

$$1, \frac{3}{2}, -\frac{5}{24}, \frac{7}{36}, -\frac{439}{1920}, \frac{1631}{5400}, -\frac{41483}{967680}, \frac{14977}{23520}, \ldots.$$

11 Conclusion

We have shown that given a generating function $g(x)$ where $g(0) \neq 0$, we can associate with it a so-called "central antecedent" $G(x)$ so that

$$[x^n]g(x) = [x^n]G(x)^n.$$

Examples have been given for common sequences. For certain integer sequences, the antecedent sequence is again an integer sequence. But this is not always the case, as is evidenced for instance by the Catalan numbers. An interesting problem that remains is to characterize those integer sequences whose central antecedents are also integer sequences.

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References

[1] P. Barry, *Riordan Arrays: a Primer*, Logic Press, 2017.

[2] R. M. Corless, G. H. Gonnet, D. E. G. Hare, D. J. Jeffrey, and D. E. Knuth, On the Lambert W function, *Adv. Comput. Math.* **5** (1996), 329-–359.

[3] H. Finkel, The differential transformation method and Miller's recurrence, preprint available at https://arxiv.org/abs/1007.2178, 2010.

[4] I. M. Gessel, Lagrange inversion, preprint available at https://arxiv.org/abs/1609.05988, 2016.

[5] R. L. Graham, D. E. Knuth, and O. Patashnik, *Concrete Mathematics*, Addison-Wesley, 1994.

[6] P. Henrici, *Applied and Computational Complex Analysis*, Volume 1, John Wiley & Sons, 1988.

[7] P. Henrici, An algebraic proof of the Lagrange-Bürmann formula, *J. Math. Anal. Appl.* **8** (1964), 218–224.

[8] D. Merlini, R. Sprugnoli, and M. C. Verri, Lagrange inversion: when and how, *Acta Appl. Math.* **94** (2006), 233–249.

[9] D. Merlini, R. Sprugnoli, and M. C. Verri, The method of coefficients, *Amer. Math. Monthly* **114** (2007), 40–57.

[10] T. D. Noe, On the divisibility of generalized central trinomial coefficients, *J. Integer Sequences* **9** (2006), Article 06.2.7.

[11] L. W. Shapiro, S. Getu, W. J. Woan, and L. C. Woodson, The Riordan group, *Discr. Appl. Math.* **34** (1991), 229–239.

[12] N. J. A. Sloane et al., *The On-Line Encyclopedia of Integer Sequences*. Published electronically at https://oeis.org/, 2020.

[13] N. J. A. Sloane, The on-line encyclopedia of integer sequences, *Notices Amer. Math. Soc.* **50** (2003), 912–915.

[14] R. P. Stanley, *Enumerative Combinatorics*, Volume 2, Cambridge University Press, 2001.

[15] D. Zeilberger, The J. C. P. Miller recurrence for exponentiating a polynomial, and its q-analog, *J. Difference Equ. Appl.* **1** (1995), 57–60.

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