Pascal's Prism: Supplementary Material

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1 Recursive definition

Using a "level" index h in the recursive relation

$$a_{(1,1)} = 1;\ a_{(i,\ j)} = \binom{i+h-2}{i-1}\left(a_{(i-1,\ j)} + a_{(i-1,\ j-1)}\right) \tag{1}$$

one can generate a family of related triangles T_h for levels $h = \{1, 2, 3, \ldots, n\}$.

1					
1	1				
1	2	1			
1	3	3	1		
1	4	6	4	1	
1	5	10	10	5	1

$\mathbf{T}_1$

1					
2	2				
3	6	3			
4	12	12	4		
5	20	30	20	5	
6	30	60	60	30	6

$\mathbf{T}_2$

1					
3	3				
6	12	6			
10	30	30	10		
15	60	90	60	15	
21	105	210	210	105	21

$\mathbf{T}_3$

1					
4	4				
10	20	10			
20	60	60	20		
35	140	210	140	35	
56	280	560	560	280	56

$\mathbf{T}_4$

1					
5	5				
15	30	15			
35	105	105	35		
70	280	420	280	70	
126	630	1260	1260	630	126

$\mathbf{T}_5$

1					
6	6				
21	42	21			
56	168	168	56		
126	504	756	504	126	
252	1260	2520	2520	1260	252

$\mathbf{T}_6$

Figure 1: The first six levels of Pascal's prism.

Figure 1 shows the first six rows of each of the first six triangles $\mathrm{T}_{(1..6)}$, wherein T_1 is Pascal's triangle. These T_h can be arranged sequentially into a 3-dimensional prismatic array wherein element $a_{(i,\ j)}$ of T_h is denoted by $a_{(h,\ i,\ j)}$. We refer to the infinite set of these sequentially arranged triangles as "Pascal's prism," denoted by $\mathbf{P}$. Furthermore, in the manner of a vector-valued function, a sequence of length k through $\mathbf{P}$ is defined by $\mathbf{P}\langle h(n), i(n), j(n)\rangle$ for $n = \{1,\ 2,\ 3,\ \ldots,\ k\}$. Thus, for example, with $k = 6$,

$$\mathbf{P}\langle 1, n+1, 2\rangle = \mathbf{P}\langle 1, n+1, n\rangle = \mathbf{P}\langle 2, n, 1\rangle = \mathbf{P}\langle 2, n, n\rangle = \mathbf{P}\langle n, 2, 1\rangle = \{1,\ 2,\ 3,\ 4,\ 5,\ 6\}.$$

Higher-ordered paths can also be defined in the same manner. The utility of this vector-valued notation is demonstrated in Section 3.

2 Explicit definition

In addition to the recursive approach in (1), Pascal's prism can be explicitly defined by the multinomial array $\binom{h+i}{h,\ i-j,\ j}$, $h \geq 0$, $i \geq 0$, $0 \leq j \leq i$, wherein element $a_{(h,i,j)} = \binom{h+i-2}{h-1,\ i-j,\ j-1}$. This can be visualized in terms of the figurate number triangle [10],

$$\mathbf{F} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & \cdots \\ 1 & 1 & 0 & 0 & 0 & \cdots \\ 1 & 2 & 1 & 0 & 0 & \cdots \\ 1 & 3 & 3 & 1 & 0 & \cdots \\ 1 & 4 & 6 & 4 & 1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

and the matrix enumerating the values of the multichoose function $\left(\!\binom{n}{k}\!\right), n > 0$ [11],

$$\mathbf{L} = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & \cdots \\ 1 & 2 & 3 & 4 & 5 & \cdots \\ 1 & 3 & 6 & 10 & 15 & \cdots \\ 1 & 4 & 10 & 20 & 35 & \cdots \\ 1 & 5 & 15 & 35 & 70 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}.$$

To generate $\mathbf{P}$, we consider $\mathbf{F}$ and $\mathbf{L}$ each as a collection of column vectors. For $\mathbf{F}$, vectors $j_k = \binom{n}{k-1}$, $k \geq 1$, $n = \{0,\ 1,\ 2,\ ...\}$. For $\mathbf{L}$, "level" vectors $\mathrm{j}_h = \binom{n+h-1}{h-1}$, $h \geq 1$, $n = \{1,\ 2,\ 3,\ ...\}$.

Next, define a *threaded Hadamard product*, denoted by "$\langle\circ\rangle$", such that for columns $\mathbf{A}_j$ in m×n matrix $\mathbf{A}$, and columns $\mathbf{B}_j$ in m×p matrix $\mathbf{B}$, an m×p×n array is produced:

$$\mathbf{A}\langle\circ\rangle\mathbf{B} = \{\{\mathbf{A}_1 \circ \mathbf{B}_1,\ \mathbf{A}_1 \circ \mathbf{B}_2, \ldots,\ \mathbf{A}_1 \circ \mathbf{B}_p\}, \quad (2)$$
$$\{\mathbf{A}_2 \circ \mathbf{B}_1,\ \mathbf{A}_2 \circ \mathbf{B}_2, \ldots,\ \mathbf{A}_2 \circ \mathbf{B}_p\}, \cdots, \{\mathbf{A}_n \circ \mathbf{B}_1,\ \mathbf{A}_n \circ \mathbf{B}_2, \ldots,\ \mathbf{A}_n \circ \mathbf{B}_p\}\}\ .$$

Then,

$$\mathbf{L}\langle\circ\rangle\mathbf{F} = \mathbf{P}\ . \tag{3}$$

Unlike the Hadamard product, the threaded Hadamard product is non-commutative.

It is interesting to note that the entire 3-dimensional array $\mathbf{P}$ can also be described in terms of the iterated convolution of the simplest sequence of positive numbers with itself. Let either row or column $\mathrm{v}_0 = \{1, 1, 1, 1, 1, ...\}$ and $\mathrm{v}_n = \mathrm{v}_0 \otimes \mathrm{v}_{(n-1)}$. Then $\mathbf{L} = \{v_0, \mathrm{v}_1, \mathrm{v}_2, \ldots, \mathrm{v}_n\}$ and $\mathbf{F}$ is formed from its padded skew diagonals.

3 Some sample sequences

Using the definition of the multinomial function, it is easy to show that, for $n = \{1,\ 2,\ 3,\ \ldots\}$, $a_{(h,\ n+j-1,\ j)} = a_{(n,\ h+j-1,\ j)}$. Thus any column j belonging to an individual level can be expressed as a pillar that orthogonally traverses levels. While each level can be studied in its own right, we will only consider a sample of sequences that traverse the diagonals of $\mathbf{P}$ as a whole.

First, $\mathbf{P}$ appears to offer a framework for uniting many related triangular and square arrays. For instance, sequences of the form $\mathbf{P}\langle n, n+k, n\rangle,\ k \geq 1$, relate to the enumeration of Schröder paths [12] and constitute the columns of OEIS sequence A104684 and its mirror image, A063007, wherein column j is given by $\frac{(2n+j-1)!}{(j-1)!n!^2}$, for $n = \{1, 2, 3, \ldots\}$.

Sequences of the form $\mathbf{P}\langle n, n+k, n+k\rangle,\ k \geq 1$, relate to the expansion of Chebyshev polynomials [8] and the enumeration of Dyck paths [9]. They constitute the non-zero entries in the columns of A100257 (see also A008311).

Sequences of the form $\mathbf{P}\langle k(n-1)+1, n, n\rangle,\ k \geq 1$, constitute the rows of A060539, the triangle enumerating $\binom{nk}{k}$. Its main diagonal (or central values) A014062 are given by $\mathbf{P}\langle n^2-n+1, n+1, n+1\rangle$.

$\mathbf{P}$ also contains many specific sequences of interest. For example, the following sequences appear in Ramanujan's theory of elliptic functions [1]:

- $\mathbf{P}\langle n, 2n-1, n\rangle = \{1, 6, 90, 1680, 34650, \ldots\}$, associated with signature 3 [5]
- $\mathbf{P}\langle n, 3n-2, n\rangle = \{1, 12, 420, 18480, 900900, \ldots\}$, associated with signature 4 [2]
- $\mathbf{P}\langle 3n-2, 3n-2, n\rangle = \{1, 60, 13860, 4084080, 1338557220, \ldots\}$, associated with signature 6 [6].

The sequence associated with signature 2 is simply $\mathbf{P}\langle n, n, n\rangle^2 = \{1, 4, 36, 400, 4900, \ldots\}$ [3].

Because it is itself composed of a family of triangles, the series of sequences for 1) the row sums, and 2) the row products of the respective levels of $\mathbf{P}$ can be compiled in to master rectangular arrays (see Figure 2).

$$\begin{pmatrix} 1 & 2 & 4 & 8 & 16 & \cdots \\ 1 & 4 & 12 & 32 & 80 & \cdots \\ 1 & 6 & 24 & 80 & 240 & \cdots \\ 1 & 8 & 40 & 160 & 560 & \cdots \\ 1 & 10 & 60 & 280 & 1120 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \qquad \begin{pmatrix} 1 & 1 & 2 & 9 & 96 & \cdots \\ 1 & 4 & 54 & 2304 & 300000 & \cdots \\ 1 & 9 & 432 & 900000 & 72900000 & \cdots \\ 1 & 16 & 2000 & 1440000 & 5042100000 & \cdots \\ 1 & 25 & 6760 & 13505625 & 161347200000 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Figure 2: Array of row sums (left) and row products (right) for the first 5 levels of $\mathbf{P}$.

While only the first row and first two columns of the row products array are familiar sequences, in the case of the row sums array, we find a rich collection of well-known sequences. The first five rows correspond respectively to A000079, A001787, A001788, A001789, and A003472, and for row h are given by $\mathrm{a}_h(\mathrm{n})= 2^{(n-h)}\binom{n}{h},\ n \geq h$. The first five columns correspond respectively to sequences A000012, A005843, A046092, A130809, and A130810 and for column j are given by $\mathrm{a}_j(\mathrm{n})= 2^j\binom{n}{n-j},\ n \geq j$.

In addition, its main diagonal is given by A059304, the first superdiagonal by A069723 (beginning with the second term), and the first subdiagonal by A069720. The skew diagonals together form A013609, the triangle which enumerates the coefficients in the expansion of $(1+2x)^n$.

Finally, in examining the overall structure of $\mathbf{P}$, we find the sequence of sums of the shallow diagonals of each level correspond to consecutive convolutions of the Fibonacci series with itself. For level h, the sums are given by the generating function $1/(1-x-x^2)^h$ and collectively form the rows of the skew Fibonacci-Pascal triangle [7].

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