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GENERALIZATIONS OF THE FIBONACCI AND LUCAS POLYNOMIALS

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Abstract

In this note we consider two sequences of polynomials, which are denoted by $\{U_{n,m}^{(k)}\}$ and $\{V_{n,m}^{(k)}\}$, where k,m,n are nonnegative integers, and $m \geq 2$. These sequences represent generalizations of the well-known Fibonacci and Lucas polynomials. For example, if $m=2$, then we obtain exactly the Fibonacci and Lucas polynomials. If $m=3$, then polynomials $U_{n,3}^{(k)}$ and $V_{n,3}^{(k)}$ were considered in papers (G. B. Djordjević, Fibonacci Quart. 39.2(2001), and G. B. Djordjević, Fibonacci Quart. 43.4(2005)).

1 Introduction

The Fibonacci and Lucas polynomials are well-known and widely investigated. In this paper we consider a more general situation, by investigating polynomials $U_{n,m}$ and $V_{n,m}$, where all polynomials are polynomials in a real variable x, and m,n are nonnegative integers, $m \geq 2$. Recall that polynomials $U_{n,m}$ and $V_{n,m}$, respectively, are defined by recurrence relations (see [1, 2]):

$$U_{n,m} = xU_{n-1,m} + U_{n-m,m}, \quad n \geq m, \tag{1.1}$$

with $U_{0,m}=0,\ U_{n,m}=x^{n-1},\ n=1,2,\ldots,m-1$, and

$$V_{n,m} = xV_{n-1,m} + V_{n-m,m}, \quad n \geq m, \tag{1.2}$$

with $V_{0,m}=2,\ V_{n,m}=x^n,\ n=1,\ldots,m-1,\ m\geq 2$ and x is a real variable. In this case corresponding generating functions are given by:

$$U^m(t) = \frac{t}{1-xt-t^m} = \sum_{n=0}^{\infty} U_{n,m}\, t^n \tag{1.3}$$

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$$V^m(t) = \frac{2 - xt}{1 - xt - t^m} = \sum_{n=0}^{\infty} V_{n,m}\, t^n. \tag{1.4}$$

It is easy to obtain the equality

$$V_{n,m} = U_{n+1,m} + U_{n+1-m,m}, \quad n \geq m - 1.$$

We denote by $U_{n,m}^{(k)}$ and $V_{n,m}^{(k)}$, respectively, derivatives of the k^{th} order of polynomials $U_{n,m}$ and $V_{n,m}$, i.e.

$$U_{n,m}^{(k)} = \frac{d^k}{dx^k}\{U_{n,m}\} \quad \text{and} \qquad V_{n,m}^{(k)} = \frac{d^k}{dx^k}\{V_{n,m}\}.$$

For given real x, we take complex numbers $\alpha_1,\ \alpha_2,\ \ldots, \alpha_m$, such that they satisfy:

$$\sum_{i=1}^{m} \alpha_i = x,\ \sum_{i<j} \alpha_i\alpha_j = 0,\ \sum_{i<j<k} \alpha_i\alpha_j\alpha_k = 0, \ldots, \alpha_1 \cdots \alpha_m = (-1)^{n-1}, \tag{1.5}$$

where $i, j, k \in \{1, 2, \ldots, m\}$. For $m = 4$, equalities (1.5) yield:

$$\sum_{i=1}^{4} \alpha_i = x,\ \sum_{i<j} \alpha_i\alpha_j = 0,\ \sum_{i<j<k} \alpha_i\alpha_j\alpha_k = 0,\ \alpha_1\alpha_2\alpha_3\alpha_4 = -1, \tag{1.6}$$

for $i, j, k \in \{1, 2, 3, 4\}$.

If $m = 2$, then we obtain exactly the Fibonacci and Lucas polynomials. If $m = 3$, then polynomials $U_{n,3}^{(k)}$ and $V_{n,3}^{(k)}$ were considered in papers [1] and [2]. In Section 2 we investigate polynomials $U_{n,4}^{(k)}$, and in Section 3 we consider the general case of polynomials $U_{n,n}^{(k)}$. In Section 4 we prove some related identities.

2 Polynomials $U_{n,4}^{(k)}$

In this section we investigate polynomials $U_{n,4}^{(k)}$, which are a special case of polynomials $U_{n,m}^{(k)}$. From (1.1), for $m = 4$, we get

$$U_{n,4} = xU_{n-1,4} + U_{n-4,4}, \quad n \geq 4, \tag{2.1}$$

with initial values $U_{0,4} = 0,\ U_{1,4} = 1,\ U_{2,4} = x,\ U_{3,4} = x^2$. Hence, by (1.3), we have that $U^4(t)$ is the corresponding generating function

$$U^4(t) = \frac{t}{1 - xt - t^4} = \sum_{n=0}^{\infty} U_{n,4}\, t^n. \tag{2.2}$$

Differentiating both sides of (2.2) k times with respect to x, we obtain

$$U_k^4(t) = \frac{k!\, t^{k+1}}{(1 - xt - t^4)^{k+1}} = \sum_{n=0}^{\infty} U_{n,4}^{(k)}\, t^n. \tag{2.3}$$

Now, we prove the following result.

Theorem 2.1. *For a nonnegative integer k the following holds:*

$$U_k^4(t) = \frac{k!}{(\alpha_1 A_{10}^1)^{k+1}} \sum_{i=0}^{k} \frac{a_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}} \tag{2.4}$$

$$+\frac{k!}{(\alpha_2 A_{10}^2)^{k+1}} \sum_{i=0}^{k} \frac{a_{k,i}^2}{(1-\alpha_2 t)^{k+1-i}} \tag{2.5}$$

$$+\frac{k!}{(\alpha_3 A_{10}^3)^{k+1}} \sum_{i=0}^{k} \frac{a_{k,i}^3}{(1-\alpha_3 t)^{k+1-i}} \tag{2.6}$$

$$+\frac{k!}{(\alpha_4 A_{10}^4)^{k+1}} \sum_{i=0}^{k} \frac{d_{k,i}}{(1-\alpha_4 t)^{k+1-i}}, \tag{2.7}$$

where

$$A_{10}^r = A_{10}^r(\alpha_r) = \frac{3\alpha_r^4 - 2\alpha_r^3 x + 1}{\alpha_r^4},\ A_{11}^r = A_{11}^r(\alpha_r) = \frac{3\alpha_r^3 x - 3\alpha_r^4 - 3}{\alpha_r^4},$$
$$A_{12}^r = A_{12}^r(\alpha_r) = \frac{\alpha_r^4 - \alpha_r^3 x + 3}{\alpha_r^4},\ A_{13}^r = A_{13}^r(\alpha_r) = -\frac{1}{\alpha_r^4},$$

$$a_{k,i}^r = (-1)^i (A_{10}^r)^i \binom{k+1}{i} -$$
$$\sum_{j=1}^{i} \sum_{l=0}^{[j/2]} \sum_{s=0}^{j-2l} \binom{k+1}{j} \binom{j-l-s}{l} \binom{l}{s} (A_{10}^r)^{l+s} (A_{11}^r)^{j-2l} (A_{12}^r)^{l-s} (A_{13}^r)^s a_{k,i-j},$$

$r = 1, 2, 3, 4$.

Proof. Using the equality (1.6), we get

$$\frac{t^{k+1}}{(1-xt-t^4)^{k+1}} \tag{2.8}$$

$$= \frac{t^{k+1}}{(1-\alpha_1 t)^{k+1}(1-\alpha_2 t)^{k+1}(1-\alpha_3 t)^{k+1}(1-\alpha_4 t)^{k+1}} \tag{2.9}$$

$$= \sum_{i=0}^{k} \frac{a_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}} + \sum_{i=0}^{k} \frac{a_{k,i}^2}{(1-\alpha_2 t)^{k+1-i}} \tag{2.10}$$

$$+ \sum_{i=0}^{k} \frac{a_{k,i}^3}{(1-\alpha_3 t)^{k+1-i}} + \sum_{i=0}^{k} \frac{a_{k,i}^4}{(1-\alpha_4 t)^{k+1-i}}. \tag{2.11}$$

Multiplying both sides of (2.8)– (2.11) with

$$\alpha_1^{k+1}(1-\alpha_2 t)^{k+1}(1-\alpha_3 t)^{k+1}(1-\alpha_4 t)^{k+1} \tag{2.12}$$

we get the following equality

$$\frac{(\alpha_1 t)^{k+1}}{(1-\alpha_1 t)^{k+1}} = \alpha_1^{k+1}\left(A_{10}^1 + A_{11}^1(1-\alpha_1 t) + A_{12}^1(1-\alpha_1 t)^2\right. \tag{2.13}$$

$$\left.+A_{13}^1(1-\alpha_1 t)^3\right)^{k+1} \sum_{i=0}^{k} \frac{A_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}} + \Phi_1(t), \tag{2.14}$$

($\Phi_1(t)$ is an analytic function at the point $t=\alpha_1^{-1}$, t is a complex variable and x is a real constant.) On the other hand, we see that:

$$\frac{(\alpha_1 t)^{k+1}}{(1-\alpha_1 t)^{k+1}}\left((1-\alpha_1 t)^{-1}-1\right)^{k+1} = \sum_{i=0}^{k+1}\binom{k+1}{i}(-1)^i(1-\alpha_1 t)^{-(k+1-i)}, \tag{2.15}$$

so

$$\begin{aligned}
&\sum_{i=0}^{k+1}\binom{k+1}{i}(-1)^i(1-\alpha_1 t)^{-(k+1-i)}\\
&=\alpha_1^{k+1}\left(A_{10}^1 + A_{11}^1(1-\alpha_1 t) + A_{12}^1(1-\alpha_1 t)^2 + A_{13}^1(1-\alpha_1 t)^3\right)^{k+1}\times\\
&\times\sum_{i=0}^{k}\frac{A_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}} + \Phi_1(t)\\
&=\alpha_1^{k+1}\sum_{j=0}^{k+1}\sum_{l=0}^{j}\sum_{s=0}^{l}\binom{k+1}{j}\binom{j}{l}\binom{l}{s}(A_{10}^1)^{k+1-j}(A_{11}^1)^{j-l}(A_{12}^1)^{l-s}A_{13}^s\times\\
&\times(1-\alpha_1 t)^{l+j+s}\sum_{i=0}^{k}\frac{A_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}} + \Phi_1(t).
\end{aligned}$$

Because the Laurent series is unique at the point $t=\alpha_1^{-1}$ for the function $(\alpha_1 t)^{-(k+1)}\left(1-\alpha_1 t\right)^{-(k+1)}$, from the last equality, and $l+j+s := j$, $j-l := j-2l-s$, we get:

$$\begin{aligned}
&\sum_{i=0}^{k+1}(-1)^i\binom{k+1}{i}\left(1-\alpha_1 t\right)^{-(k+1-i)}\\
&=\alpha_1^{k+1}\sum_{j=0}^{k+1}\sum_{l=0}^{j}\sum_{s=0}^{j-2l}\binom{k+1}{i}\binom{j-l-s}{l}\binom{l}{s}(A_{10}^1)^{k+1-j+l+s}(A_{11}^1)^{j-2l-s}\times\\
&\times(A_{12}^1)^{l-s}(A_{13}^1)^s\sum_{i=0}^{k}\frac{A_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}} + \Phi_1(t).
\end{aligned}$$

Comparing coefficients with respect to $(1-\alpha_1 t)^{-(k+1-i)}$, we find that:

$$(-1)^i (A_{10}^1)^i \binom{k+1}{i} = \alpha_1^{k+1} \sum_{j=0}^{i} \sum_{l=0}^{j} \sum_{s=0}^{j-2l} \binom{k+1}{j} \binom{j-l-s}{l} \binom{l}{s} \times$$
$$\times (A_{10}^1)^{k+1+i-j} (A_{10}^1)^{l+s} (A_{11}^1)^{j-2l-s} (A_{12}^1)^{l-s} (A_{13}^1)^s A_{k,i-j}^1.$$

Hence, for

$$\alpha_1^{k+1} (A_{10}^1)^{k+1+i-j} A_{k,i-j}^1 = a_{k,i-j}^1,$$

we get

$$(-1)^i (A_{10}^1)^i \binom{k+1}{i} =$$
$$\sum_{j=0}^{i} \sum_{l=0}^{[j/2]} \sum_{s=0}^{j-2l} \binom{k+1}{j} \binom{j-l-s}{l} \binom{l}{s} (A_{10}^1)^{l+s} (A_{11}^1)^{j-2l} (A_{12}^1)^{l-s} (A_{13}^1)^s a_{k,i-j}^1.$$

It follows that

$$a_{k,i}^1 = (-1)^i (A_{10}^1)^i \binom{k+1}{i} -$$
$$\sum_{j=1}^{i} \sum_{l=0}^{[j/2]} \sum_{s=0}^{j-2l} \binom{k+1}{j} \binom{j-l-s}{l} \binom{l}{s} (A_{10}^1)^{l+s} (A_{11}^1)^{j-2l} (A_{12}^1)^{l-s} (A_{13}^1)^s a_{k,i-j}^1.$$

In a similar way, we find the remaining coefficients $a_{k,i}^r$, $r = 1, 2, 3, 4$:

$$a_{k,i}^r = (-1)^i (A_{10}^r)^i \binom{k+1}{i}$$
$$-\sum_{j=1}^{i} \sum_{l=0}^{[j/2]} \sum_{s=0}^{j-2l} \binom{k+1}{j} \binom{j-l-s}{l} \binom{l}{s} (A_{10}^r)^{l+s} (A_{11}^r)^{j-2l} (A_{12}^r)^{l-s} (A_{13}^r)^s a_{k,i-j}^r.$$

Coefficients A_{10}^1, A_{11}^1, A_{12}^1, A_{13}^1 can be computed from the following equalities

$$A_{10}^1 + A_{11}^1(1-\alpha_1 t) + A_{12}^1(1-\alpha_1 t)^2 + A_{13}^1(1-\alpha_1 t)^3 = (1-\alpha_2 t)(1-\alpha_3 t)(1-\alpha_4 t) \quad (2.16)$$

and using (1.6).

In a similar way, we find the remaining coefficients A_{10}^r, A_{11}^r, A_{12}^r, A_{13}^r, $r = 2, 3, 4$.

□

3 Polynomials $U_{n,m}^{(k)}$

In this section we investigate polynomials $U_{n,m}^{(k)}$. Differentiating (1.3), k-times with respect to x, we obtain

$$U_m^k(t) = \frac{k! t^{k+1}}{(1 - xt - t^m)^{k+1}} = \sum_{n=0}^{\infty} U_{n,m}^{(k)} t^n. \quad (3.1)$$

Theorem 3.1. *Let k be a nonnegative integer, and let m be a positive integer, $m \geq 2$. Then*

$$U_k^m(t) = \sum_{j=1}^{m} \frac{k!}{(\alpha_j A_{10}^j)^{k+1}} \sum_{i=0}^{k} \frac{a_{k,i}^j}{(1-\alpha_j t)^{k+1-i}}, \tag{3.2}$$

where:

$$\begin{aligned} A_{10}^j + \quad & A_{11}^j(1-\alpha_j t) + A_{12}^j(1-\alpha_j t)^2 + \cdots + A_{1,m-1}^j(1-\alpha_j t)^{m-1} \\ & = (1-\alpha_1 t)(1-\alpha_2 t)\cdots(1-\alpha_{j-1}t)(1-\alpha_{j+1}t)\cdots(1-\alpha_m t), \end{aligned}$$

and $\alpha_1, \ldots, \alpha_m$ satisfy equalities (1.5)*;*

$$a_{k,i}^j = (-1)^i (A_{10}^j)^i \binom{k+1}{i} - \tag{3.3}$$

$$\sum_{j_1=1}^{i} \sum_{j_2=0}^{j_1} \cdots \sum_{j_{m-1}=0}^{j_{m-2}} \binom{k+1}{j_1}\binom{j_1}{j_2}\cdots\binom{j_{m-2}}{j_{m-1}} (A_{10}^j)^{j_2+\cdots+j_{m-1}} \times \tag{3.4}$$

$$(A_{11}^j)^{j_1-j_2} \cdots \times (A_{1,m-1}^j)^{j_{m-1}} a_{k,i-j_1}^j, \;\; j = 1, 2, \ldots, m. \tag{3.5}$$

Proof. From (3.1) and (1.5) we obtain:

$$\frac{t^{k+1}}{(1-xt-t^m)^{k+1}} = \frac{t^{k+1}}{(1-\alpha_1 t)^{k+1}\cdots(1-\alpha_m)^{k+1}} \tag{3.6}$$

$$= \sum_{i=0}^{k} \frac{A_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}} + \sum_{i=0}^{k} \frac{A_{k,i}^2}{(1-\alpha_2 t)^{k+1-i}} + \ldots \tag{3.7}$$

$$+ \sum_{i=0}^{k} \frac{A_{k,i}^m}{(1-\alpha_m t)^{k+1}}. \tag{3.8}$$

Multiplying (3.6)–(3.8) with $\alpha_1^{k+1}(1-\alpha_2 t)^{k+1}\cdots(1-\alpha_m t)^{k+1}$, we have the following equality

$$\frac{(\alpha_1 t)^{k+1}}{(1-\alpha_1 t)^{k+1}} = \alpha_1^{k+1}\left(A_{10}^1 + A_{11}^1(1-\alpha_1 t) + A_{12}^1(1-\alpha_1 t)^2 + \ldots \right. \tag{3.9}$$

$$\left. + A_{1,m-1}^1(1-\alpha_1 t)^{m-1}\right)^{k+1} \sum_{i=0}^{k} \frac{A_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}} + \Phi_1(t), \tag{3.10}$$

($\Phi_1(t)$ is an analytic function at $t = \alpha_1^{-1}$; t is a complex variable; x is a real constant.) The left side of the equality (3.9) can be rewritten in the following form:

$$\frac{(\alpha_1 t)^{k+1}}{(1-\alpha_1 t)^{k+1}} = \left((1-\alpha_1 t)^{-1} - 1\right)^{k+1} = \sum_{i=0}^{k+1} (-1)^i \binom{k+1}{i} (1-\alpha_1 t)^{-(k+1-i)}. \tag{3.11}$$

The right side of the same equality is

$$\alpha_1^{k+1}\sum_{j_1=0}^{k+1}\sum_{j_1=0}^{j_1}\cdots\sum_{j_{m-1}}^{j_{m-2}}\binom{k+1}{j_1}\binom{j_1}{j_2}\cdots\binom{j_{m-1}}{j_{m-2}}(A_{10}^1)^{k+1-j_1}(A_{11}^1)^{j_1-j_2}\cdots \tag{3.12}$$

$$\times(A_{1,m-1}^1)^{j_{m-1}}(1-\alpha_1 t)^{j_1+\cdots+j_{m-1}}\sum_{i=0}^{k}\frac{A_{k,i}^1}{(1-\alpha_1 t)^{k+1-i}}+\Phi_1(t). \tag{3.13}$$

First taking

$$\alpha_1^{k+1}(A_{10}^1)^{k+1+i-j_1}A_{k,i-j_1}^1 = a_{k,i-j_1}^1, \text{ and } j_1+j_2+\cdots+j_{m-1} := j_1,$$

comparing coefficients with respect to $(1-\alpha_1 t)^{-(k+1-i)}$, and then using (3.11) and (3.12), we obtain coefficients $a_{k,i}^1$. Similarly, we compute other coefficients, $a_{k,i}^j$, $j=1,2,\ldots,j_{m-1}$. $\square$

4 Some identities

In this section we prove some identities, for generalized polynomials $U_{n,m}^{(k)}$ and $V_{n,m}^{(k)}$. For $m=2$, these identities correspond to the Fibonacci and Lucas polynomials. For $m=3$, these identities correspond to generalized polynomials, which are considered in [1] and [2].

Lemma 4.1. *For positive integers m,n, such that $n\ge m\ge 2$, the following hold:*

$$\sum_{i=0}^{n}U_{i,m}=\frac{1}{x}\left(\sum_{j=0}^{m-1}U_{n+2-m+j,m}-1\right), \tag{4.1}$$

$$\sum_{i=0}^{n}V_{i,m}=\frac{1}{x}\left(\sum_{j=0}^{m-1}V_{n+2-m+j,m}-1\right), \tag{4.2}$$

$$\sum_{i=0}^{n} \binom{n}{i} x^i h_{r+(m-1)i,m} = h_{r+mn,m}, \tag{4.3}$$

$$\sum_{i=0}^{n} \binom{n}{i} (-1)^i h_{r+mi,m} = (-1)^n x^n h_{r+(m-1)n,m}, \tag{4.4}$$

where $h_{n,m} = U_{n,m}$, *or* $h_{n,m} = V_{n,m}$.

Proof. We use the induction on n. It is easy to see that (4.1) is satisfied for $n = 1$. Suppose that the equality (4.1) is valid for n, then (for $n := n+1$):

$$\begin{aligned}
\sum_{i=0}^{n+1} U_{i,m} &= \frac{1}{x}\left(\sum_{j=0}^{m-1} U_{n+2-m+j,m} - 1\right) + U_{n+1,m} \\
&= \frac{1}{x}\left(\sum_{j=0}^{m-1} U_{n+2-m+j,m} - 1 + xU_{n+1,m}\right) \quad (\text{by } (1.1)) \\
&= \frac{1}{x}\left(\sum_{j=0}^{m-1} U_{n+3-m+j,m} - 1\right).
\end{aligned}$$

Hence, the equality (4.1) holds for any positive integer n.

The equality (4.2) can be proved in a similar way, using the recurrence relation (1.2).

Suppose that (4.3) holds for n. Then, taking the value $n+1$ instead of n, from (1.1) and (1.2), we get:

$$\begin{aligned}
&h_{r+m(n+1),m} = xh_{r+mn+m-1,m} + h_{r+mn,m} \\
&= \sum_{i=0}^{n} \binom{n}{i} x^i h_{r+(m-1)i,m} + xh_{r+mn+m-1,m} \\
&= \sum_{i=0}^{n} \binom{n}{i} x^i h_{r+(m-1)i,m} + x\sum_{i=0}^{n} \binom{n}{i} x^i h_{r+m-1+(m-1)i,m} \\
&= \sum_{i=0}^{n} \binom{n}{i} x^i h_{r+(m-1)i,m} + \sum_{i=1}^{n+1} \binom{n}{i-1} x^i h_{r+(m-1)i,m} = \\
&\sum_{i=1}^{n} \left(\binom{n}{i} + \binom{n}{i-1}\right) x^i h_{r+(m-1)i,m} + h_{r,m} + x^{n+1} h_{r+(m-1)(n+1),m} \\
&= \sum_{i=1}^{n} \binom{n+1}{i} x^i h_{r+(m-1)i,m} + \binom{n+1}{0} h_{r,m} + \binom{n+1}{n+1} h_{r+(m-1)(n+1),m} \\
&= \sum_{i=0}^{n+1} \binom{n+1}{i} x^i h_{r+(m-1)i,m}.
\end{aligned}$$

Now, we have proved the equality (4.3).

Suppose that (4.4) is correct for n. Then

$$\begin{aligned}
&(-1)^{n+1}x^{n+1}h_{r+(m-1)(n+1),m} = (-1)^{n+1}x^n(xh_{r+m-1+(m-1)n,m})\\
&= (-1)^{n+1}x^n(h_{r+m+(m-1)n,m} - h_{r+(m-1)n,m})\\
&= (-1)^{n+1}x^n h_{r+m+(m-1)n,m} + (-1)^n x^n h_{r+(m-1)n,m}\\
&= \sum_{i=0}^{n}(-1)^{i+1}\binom{n}{i}h_{r+m(i+1),m} + \sum_{i=0}^{n}(-1)^i\binom{n}{i}h_{r+mi,m}\\
&= \sum_{i=1}^{n}(-1)^i\left(\binom{n}{i-1}+\binom{n}{i}\right)h_{r+mi,m} + h_{r,m} + (-1)^{n+1}h_{r+m(n+1),m}\\
&= \sum_{i=0}^{n+1}(-1)^i\binom{n+1}{i}h_{r+mi,m}.
\end{aligned}$$

□

Theorem 4.1. *For positive integers m, n, such that $n \ge m \ge 2$, the following equalities hold:*

$$x\sum_{i=0}^{n}U_{i,m}^{(k)} = \sum_{j=0}^{m-1}U_{n+2-m+j,m}^{(k)} - k\sum_{i=0}^{n}U_{i,m}^{(k-1)},\ \ k \ge 1. \tag{4.5}$$

$$x\sum_{i=0}^{n}V_{i,m}^{(k)} = \sum_{j=0}^{m-1}V_{n+2-m+j,m}^{(k)} - k\sum_{i=0}^{n}V_{i,m}^{(k-1)},\ \ k \ge 1. \tag{4.6}$$

$$\sum_{i=0}^{n}\sum_{j=0}^{k}\binom{n}{i}\binom{k}{j}(x^i)^{(j)}h_{r+(m-1)i,m}^{(k-j)} = h_{r+mn,m}^{(k)}, \tag{4.7}$$

$$\sum_{i=0}^{n}(-1)^i\binom{n}{i}h_{r+mi,m}^{(k)} = (-1)^n\sum_{j=0}^{k}\binom{k}{j}(n-j+1)_j x^{n-j}h_{r+(m-1)n,m}^{(k-j)}. \tag{4.8}$$

where $h_{r,m} = U_{r,m}$ or $h_{r,m} = V_{r,m}$.

Proof. Differentiating both sides of equalities (4.1) and (4.2), on x, k–times, we obtain equalities (4.5) and (4.6). Using the induction on k, we prove (4.7). If $k = 0$, then (4.7) becomes

$$h_{r+mn,m} = \sum_{i=0}^{n}\binom{n}{i}x^i h_{r+(m-1)i,m},$$

so, we get the equality (4.7). Suppose that (4.7) holds for k ($k \ge 0$). Then, for

$k := k+1$, we get

$$h^{(k+1)}_{r+mn,m} = \sum_{i=0}^{n}\sum_{j=0}^{k}\binom{n}{i}\binom{k}{j}\frac{d}{dx}\left((x^i)^{(j)}h^{(k-j)}_{r+(m-1)i,m}\right) =$$

$$\sum_{i=0}^{n}\sum_{j=0}^{k}\binom{n}{i}\binom{k}{j}\left((x^i)^{(j+1)}h^{(k-j)}_{r+(m-1)i,m} + (x^i)^{(j)}h^{(k+1-j)}_{r+(m-1)i,m}\right)$$

$$\sum_{i=0}^{n}\sum_{j=1}^{k+1}\binom{n}{i}\binom{k}{j-1}(x^i)^{(j)}h^{(k+1-j)}_{r+(m-1)i,m} + \sum_{i=0}^{n}\sum_{j=0}^{k}\binom{n}{i}\binom{k}{j}(x^i)^{(j)}h^{(k+1-j)}_{r+(m-1)i,m}$$

$$= \sum_{i=0}^{n}\sum_{j=1}^{k}\binom{n}{i}\binom{k+1}{j}(x^i)^{(j)}h^{(k+1-j)}_{r+(m-1)i,m} + \sum_{i=0}^{n}\binom{n}{i}x^i h^{(k+1)}_{r+(m-1)i,m} +$$

$$\sum_{i=0}^{n}\binom{n}{i}(x^i)^{(k+1)}h_{r+(m-1)i,m} = \sum_{i=0}^{n}\sum_{j=0}^{k+1}\binom{n}{i}\binom{k+1}{j}(x^i)^{(j)}h^{(k+1-j)}_{r+(m-1)i,m}.$$

So, we have proved the equality (4.7). Similarly, we can get the equality (4.8). $\square$

Further, we prove some equalities, using generating functions (1.3) and (1.4). Precisely, if we differentiate (1.4) k-times with respect to x, then we obtain

$$V^m_k(t) = \frac{k!t^k(1+t^m)}{(1-xt-t^m)^{k+1}} = \sum_{n=0}^{\infty} V^{(k)}_{n,m}\, t^n. \tag{4.9}$$

Using (3.1) and (4.9), we can easily prove the following theorem.

Theorem 4.2. *For integers m, k, r, such that $m \geq 2$, and $k, r \geq 0$, the following hold:*

$$U^m_k(t)U^m_r(t) = \frac{k!r!}{(k+r+1)!}U^m_{k+r+1}(t), \tag{4.10}$$

$$U^m_k(t)V^m(t) = \frac{2t^{-1}-x}{k+1}U^m_{k+1}(t), \tag{4.11}$$

$$V^m_k(t)V^m_r(t) = \frac{k!r!}{(k+r+1)!}V^m_{k+r+1}(t^{-1}+t^{m-1}),\ (r,k \geq 1), \tag{4.12}$$

$$U^m_k(t)V^m_r(t) = \frac{k!r!}{(k+r+1)!}V^m_{k+r+1}(t),\ (r,k \geq 1), \tag{4.13}$$

$$V^m_k(t)V(t) = \frac{1}{k+1}(2t^{-1}-x)V^m_{k+1}(t), \tag{4.14}$$

$$V^m(t)V^m(t) = (2t^{-1}-x)^2U^m_1(t). \tag{4.15}$$

The following result is an immediate consequence of Theorem 4.2:

Theorem 4.3. *Let m, n, k be integers, such that $n \geq m \geq 2$ and $k \geq 0$. Then*

$$\sum_{i=0}^{n} U_{i,m}^{(k)} U_{n-i,m}^{(r)} = \frac{k!r!}{(k+r+1)!} U_{n,m}^{(k+r+1)}, \tag{4.16}$$

$$\sum_{i=0}^{n} U_{i,m}^{(k)} V_{n-i,m} = \frac{1}{k+1} \left(2U_{n+1,m}^{(k+1)} - xU_{n,m}^{(k+1)} \right), \tag{4.17}$$

$$\sum_{i=0}^{n} V_{i,m}^{(k)} V_{n-i,m}^{(r)} = \frac{k!r!}{(k+r+1)!} \left(V_{n+1,m}^{(k+r+1)} + V_{n+1-m,m}^{(k+r+1)} \right), \tag{4.18}$$

$$\sum_{i=0}^{n} U_{i,m}^{(k)} V_{n-i,m}^{(r)} = \frac{k!r!}{(k+r+1)!} V_{n,m}^{(k+r+1)}, \ (r \geq 1), \tag{4.19}$$

$$\sum_{i=0}^{n} V_{i,m}^{(k)} V_{n-i,m} = \frac{1}{k+1} \left(2V_{n+1,m}^{(k+1)} - xV_{n,m}^{(k+1)} \right), \tag{4.20}$$

$$\sum_{i=0}^{n} V_{i,m} V_{n-i,m} = 4U_{n+2,m}^{(1)} - 4xU_{n+1,m}^{(1)} + x^2 U_{n,m}^{(1)}. \tag{4.21}$$

Proof. Comparing coefficients with respect to t^n in equalities (4.10)–(4.15), respectively, we obtain equalities (4.16)-(4.21). □

Corollary 4.1. *Equalities* (4.10)–(4.21) *for $m = 2$ and $m = 3$ correspond to the Fibonacci and Lucas polynomials, and to those considered in* [1] *and* [2].

References

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