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SOME IDENTITIES FOR CHEBYSHEV POLYNOMIALS

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Abstract: We prove a generalization of a conjectured formula of Melham and provide some background about the involved (Chebyshev) polynomials.

1 – Introduction

In [3] Melham considered the two sequences

$$\begin{aligned} U_n &= pU_{n-1} - U_{n-2}\,, \qquad U_0 = 0,\ U_1 = 1\ , \\ V_n &= pV_{n-1} - V_{n-2}\,, \qquad V_0 = 2,\ V_1 = p\ , \end{aligned}$$

and conjectured the formula

$$U_n^{2k} + U_{n+1}^{2k} = \sum_{r=0}^{k} \frac{D^r V_k}{r!}\, U_n^{k-r}\, U_{n+1}^{k-r}\ ,$$

where D means differentiation with respect to p. We remark here that up to simple changes of variable these polynomials are Chebyshev polynomials. More precisely

$$\begin{aligned} U_n(p) &= \mathcal{U}_{n-1}(\tfrac{p}{2})\ , \\ V_n(p) &= 2\mathcal{T}_n(\tfrac{p}{2})\ , \end{aligned}$$

where $\mathcal{T}_n$ and $\mathcal{U}_n$ denote the classical Chebyshev polynomials of first and second kind, respectively.

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The aim of this paper is to prove a general identity that contains Melham's conjecture as a special case: Set $W_n = aU_n + bV_n$ and $\Omega = a^2 + 4b^2 - b^2p^2$, then

$$W_n^{2k} + W_{n+1}^{2k} = \sum_{r=0}^{k} \Omega^{k-r}\, \lambda_{k,r}\, W_n^r\, W_{n+1}^r \,, \tag{1}$$

with

$$\lambda_{k,r} = \sum_{0\le 2j\le r} (-1)^j\, \frac{k(k-1-j)!}{(k-r)!\, j!\, (r-2j)!}\, p^{r-2j}$$

and $\lambda_{0,0} = 2$.

From [1, 2] we know explicit expansions for Chebyshev polynomials:

$$V_k = \sum_{0\le 2j\le k} (-1)^j \binom{k-j}{j} \frac{k}{k-j}\, p^{k-2j}$$

for $k \ge 1$ and $V_0 = 2$. Then we have

$$\lambda_{k,r} = \frac{D^{k-r}\, V_k}{(k-r)!} \,,$$

which links Melham's conjecture and (1).

2 – Proof of the Formula

We will make use of the identity

$$\sum_{t=0}^{\infty} y^t\, \frac{(a+t)!}{t!}\, (bt+c) \;=\; a!\, (1-y)^{-a-2} \Big(c + y(ab+b-c)\Big) \,, \tag{2}$$

which follows from

$$\sum_{t=0}^{\infty} \binom{a+t}{t} y^t \;=\; (1-y)^{-a} \,. \tag{3}$$

In order to prove (1) we form the generating function

$$g(z) \;=\; \sum_{k=0}^{\infty} z^k \sum_{r=0}^{k} \Omega^{k-r}\, \lambda_{k,r}\, \sigma^r$$

with $\sigma = W_n W_{n+1}$. We reorder this to obtain (setting $k-r=t$)

$$\begin{aligned} g(z) &= \sum_{r\ge 0}\sum_{k\ge r} z^k\, \Omega^{k-r} \sigma^r\, \lambda_{k,r} \;=\; \sum_{r\ge 0}\sum_{t\ge 0} z^{r+t}\, \Omega^t\, \sigma^r \lambda_{r+t,r} \\ &= \sum_{r\ge 1}\sum_{t\ge 0} z^{r+t}\, \Omega^t\, \sigma^r \lambda_{r+t,r} \;+\; 1 \;+\; \sum_{t\ge 0} z^t\, \Omega^t \qquad (\text{using } \lambda_{0,0} = 2) \end{aligned}$$

$$
\begin{aligned}
&= \sum_{r\geq 1}\sum_{t\geq 0}\sum_{0\leq 2j\leq r} z^t\,\Omega^t(\sigma z)^r(-1)^j\,\frac{(r+t)\,(r+t-1-j)!}{t!\,j!\,(r-2j)!}\,p^{r-2j} + 1 + \sum_{t\geq 0} z^t\,\Omega^t \\
&= \sum_{j\geq 1}\sum_{r\geq 2j}\sum_{t\geq 0} z^t\,\Omega^t(\sigma z)^r(-1)^j\,\frac{(r+t)\,(r+t-1-j)!}{t!\,j!\,(r-2j)!}\,p^{r-2j} \\
&\quad +1 + \sum_{r\geq 0}\sum_{t\geq 0} z^t\,\Omega^t(\sigma z)^r\,\frac{(r+t)!}{t!\,r!}\,p^r \qquad \text{(terms for } j=0 \text{ plus the last sum)} \\
&= \sum_{j\geq 1}\sum_{r\geq 2j}(-1)^j\,p^{r-2j}(\sigma z)^r(1-\Omega z)^{j-r-1}\,\frac{(r-j-1)!}{j!\,(r-2j)!}\,(r-j\,\Omega z) \qquad \text{by (2)} \\
&\quad + \sum_{r\geq 0}(p\,\sigma\,z)^r\,(1-\Omega z)^{-r-1} + 1 \qquad \text{by (3)} \\
&= \sum_{j\geq 1}\frac{(-1)^j\,(\sigma z)^{2j}}{(1-\Omega z)^{j+1}}\sum_{s\geq 0}\left(\frac{p\,\sigma\,z}{1-\Omega z}\right)^s\frac{(j+s-1)!}{j!\,s!}\Big(j(2-\Omega z)+s\Big) \qquad (r=2j+s) \\
&\quad + \frac{1}{1-(\Omega+p\,\sigma)\,z} + 1 \\
&= \sum_{j\geq 1}\frac{(-1)^j\,(\sigma z)^{2j}}{\Big(1-(\Omega+p\,\sigma)\,z\Big)^{j+1}}\Big(2-(\Omega+p\,\sigma)\,z\Big) \qquad \text{by (2)} \\
&\quad + \frac{1}{1-(\Omega+p\,\sigma)\,z} + 1 \\
&= -\frac{(\sigma z)^2\,\Big(2-(\Omega+p\,\sigma)\,z\Big)}{\Big(1-(\Omega+p\,\sigma)\,z\Big)\Big(1-(\Omega+p\,\sigma)\,z+\sigma^2 z^2\Big)} + \frac{1}{1-(\Omega+p\,\sigma)z} + 1 \\
&= \frac{2-(\Omega+p\,\sigma)z}{1-(\Omega+p\,\sigma)z+\sigma^2 z^2}\ .
\end{aligned}
$$

The generating function of the left hand side is

$$\frac{1}{1-W_n^2 z} + \frac{1}{1-W_{n+1}^2 z} = \frac{2-(W_n^2+W_{n+1}^2)z}{1-(W_n^2+W_{n+1}^2)z+W_n^2W_{n+1}^2 z^2}$$

and the assertion follows from

$$W_n^2 + W_{n+1}^2 = pW_nW_{n+1} + \Omega\ ,$$

which is easily proved e. g. by using the explicit forms

$$U_n = \frac{\alpha^n-\beta^n}{\alpha-\beta}\,, \qquad V_n = \alpha^n+\beta^n\ ,$$

with

$$\alpha = \frac{p+\sqrt{p^2-4}}{2}\,, \qquad \beta = \frac{p-\sqrt{p^2-4}}{2}\ .$$

3 – Further identities

Many other similar formulæ seem to exist; we just give one other example; set

$$a_{k,r} = \sum_{0\le\lambda\le r} (-1)^\lambda\, p^{2k-2\lambda}\, \frac{k\Big(k-\lfloor\frac{\lambda}{2}\rfloor-1\Big)!\, 2^{\lceil\frac{\lambda}{2}\rceil}}{(k-r)!\,\lambda!\,(r-\lambda)!} \prod_{i=0}^{\lfloor\frac{\lambda}{2}\rfloor-1} \Big(2k-2\Big\lceil\frac{\lambda}{2}\Big\rceil-1-2i\Big)$$

and $a_{0,0}=2$, then

$$W_n^{2k} + W_{n+2}^{2k} = \sum_{r=0}^{k} \Omega^{k-r}\, a_{k,r}\, W_n^r\, W_{n+2}^r\ .$$

The proof is as before.

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