

# NEWTON'S INTERPOLATION FORMULA AND SUMS OF POWERS

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ABSTRACT. In this manuscript we derive formulas for multifold sums of powers by utilizing Newton's interpolation formula. Furthermore, we provide formulas for multifold sums of powers in terms of Stirling numbers of the second kind and Eulerian numbers.

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## 1. INTRODUCTION AND MAIN RESULTS

In this manuscript we derive formulas for multifold sums of powers by utilizing Newton's interpolation formula. Furthermore, we provide formulas for multifold sums of powers in terms of Stirling numbers of the second kind and Eulerian numbers.

The idea to derive sums of powers using difference operator and Newton's series is quite generic, thus, formulas for sums of powers using backward and central differences can be found in the works [1, 2].

Allow us to start from the definition of multifold sums of powers. We utilize the recurrence proposed by Donald Knuth in his article *Johann Faulhaber and sums of powers*, see [3]

$$\Sigma^0 n^m = n^m$$

$$\Sigma^1 n^m = \Sigma^0 1^m + \Sigma^0 2^m + \cdots + \Sigma^0 n^m$$

$$\Sigma^{r+1} n^m = \Sigma^r 1^m + \Sigma^r 2^m + \cdots + \Sigma^r n^m$$

Throughout the paper, we utilize the Newton's interpolation formula as stated below

**Proposition 1.1.** (*Newton's interpolation formula* [4, Lemma V].)

$$f(x) = \sum_{j=0}^{\infty} \binom{x-a}{j} \Delta^j f(a)$$

where  $\Delta^k f(a) = \sum_{j=0}^k (-1)^{k-j} \binom{k}{j} f(a+j)$  are  $k$ -degree forward finite differences of  $f$  evaluated in point  $a$ .

Which is indeed true, because

$$\begin{aligned} n^3 &= 0 \binom{n}{0} + 1 \binom{n}{1} + 6 \binom{n}{2} + 6 \binom{n}{3} \\ n^3 &= 1 \binom{n-1}{0} + 7 \binom{n-1}{1} + 12 \binom{n-1}{2} + 6 \binom{n-1}{3} \\ n^3 &= 8 \binom{n-2}{0} + 19 \binom{n-2}{1} + 18 \binom{n-2}{2} + 6 \binom{n-2}{3} \end{aligned}$$

**Proposition 1.2** (Newton's series for power). *For non-negative integers  $m, n$  and an arbitrary integer  $t$*

$$n^m = \sum_{k=0}^m \binom{n-t}{k} \Delta^k t^m$$

Thus, for an arbitrary integer  $t$ , the ordinary sum of powers is

$$\Sigma^1 n^m = \sum_{k=1}^n \sum_{j=0}^m \binom{-t+k}{j} \Delta^j t^m = \sum_{j=0}^m \Delta^j t^m \sum_{k=1}^n \binom{-t+k}{j}$$

**Proposition 1.3** (Segmented Hockey stick identity). *For integers  $n, t$  and  $j$*

$$\sum_{k=0}^n \binom{-t+k}{j} = (-1)^j \binom{j+t}{j+1} + \binom{n-t+1}{j+1}$$

Hence,

$$\begin{aligned} \sum_{k=1}^n \binom{-t+k}{j} &= (-1)^j \binom{j+t}{j+1} + \binom{n-t+1}{j+1} - \binom{-t}{j} \\ &= (-1)^j \binom{j+t}{j+1} - (-1)^j \binom{j+t-1}{j} + \binom{n-t+1}{j+1} \\ &= (-1)^j \binom{j+t-1}{j+1} + \binom{n-t+1}{j+1} \end{aligned}$$

because  $\binom{-t}{j} = (-1)^j \binom{j+t-1}{j}$  and by recurrence  $\binom{t+1}{k} = \binom{t}{k} + \binom{t}{k+1}$ .

This implies formula for sums of powers

**Proposition 1.4** (Ordinary sums of powers via Newton's series). *For non-negative integers  $n, m$  and an arbitrary integer  $t$*

$$\Sigma^1 n^m = \sum_{j=0}^m \Delta^j t^m \left[ (-1)^j \binom{j+t-1}{j+1} + \binom{n-t+1}{j+1} \right]$$

*Proof.* Ordinary sum of powers is given by  $\Sigma^1 n^m = \sum_{j=0}^m \Delta^j t^m \sum_{k=1}^n \binom{-t+k}{j}$ , where  $\sum_{k=1}^n \binom{-t+k}{j} = (-1)^j \binom{j+t-1}{j+1} + \binom{n-t+1}{j+1}$  by means of segmented hockey stick identity (1.3).  $\square$

The special cases for  $t = 0$  and  $t = 1$  are widely known and appear in literature quite frequently. For  $t = 0$  and  $m = 3$  we have the famous identity

$$\Sigma^1 n^3 = 0 \binom{n+1}{1} + 1 \binom{n+1}{2} + 6 \binom{n+1}{3} + 6 \binom{n+1}{4}$$

which was discussed in [5, p. 190] and in [6].

The coefficients 0, 1, 6, 6, 0, 1, 14, 36, 24, ... is the sequence A131689 in the OEIS [7].

The special cases for  $t = 1$  and  $m = 2, 3, 4, 5$  were discussed in [8]. For instance,

$$\begin{aligned}\Sigma^1 n^3 &= 1 \binom{n}{1} + 7 \binom{n}{2} + 12 \binom{n}{3} + 6 \binom{n}{4} \\ \Sigma^1 n^4 &= 1 \binom{n}{1} + 15 \binom{n}{2} + 50 \binom{n}{3} + 60 \binom{n}{4} + 24 \binom{n}{5}\end{aligned}$$

The coefficients 1, 7, 12, 6, 1, 15, ... is the sequence A028246 in the OEIS [7].

Interestingly enough that the paper [8] gives the formula for sums of powers

$$\Sigma^1 n^k = \sum_{j=0}^k j! \left[ \binom{n+1-r}{j+1} + (-1)^j \binom{r+j-1}{j+1} \right] \left\{ \begin{matrix} k \\ j \end{matrix} \right\}_r$$

where  $\left\{ \begin{matrix} k \\ j \end{matrix} \right\}_r$  are generalized Stirling numbers of the second kind.

The formula above is identical to the proposition (1.4), which implies that finite differences can be expressed in terms of generalized Stirling numbers of the second kind, that is  $\Delta^j t^m = j! \left\{ \begin{matrix} m \\ j \end{matrix} \right\}_t$ .

By considering the special cases of the proposition (1.4) for  $t = 4$ , we observe rather unexpected formulas for sums of powers, namely

$$\begin{aligned}\Sigma^1 n^0 &= 1 \left( \binom{n-3}{1} + \binom{3}{1} \right) \\ \Sigma^1 n^1 &= 4 \left( \binom{n-3}{1} + \binom{3}{1} \right) + 1 \left( \binom{n-3}{2} - \binom{4}{2} \right) \\ \Sigma^1 n^2 &= 16 \left( \binom{n-3}{1} + \binom{3}{1} \right) + 9 \left( \binom{n-3}{2} - \binom{4}{2} \right) + 2 \left( \binom{n-2}{3} + \binom{5}{3} \right) \\ \Sigma^1 n^3 &= 64 \left( \binom{n-3}{1} + \binom{3}{1} \right) + 61 \left( \binom{n-3}{2} - \binom{4}{2} \right) + 30 \left( \binom{n-3}{3} + \binom{5}{3} \right) \\ &\quad + 6 \left( \binom{n-3}{4} - \binom{6}{4} \right)\end{aligned}$$

The coefficients 1, 4, 1, 16, 9, ... is the sequence A391633 in the OEIS [7]. In general,

$$\Sigma^1 n^m = \sum_{j=0}^m \Delta^j 4^m \left[ \binom{n-3}{j+1} + (-1)^j \binom{j+3}{j+1} \right].$$

To derive formula for double sum of powers, we apply summation operator over the ordinary sum of powers (1.4) again, thus

$$\Sigma^2 n^m = \sum_{j=0}^m \Delta^j t^m \left[ (-1)^j \sum_{k=1}^n \binom{j+t-1}{j+1} + \sum_{k=1}^n \binom{k-t+1}{j+1} \right]$$

which yields

$$\Sigma^2 n^m = \sum_{j=0}^m \Delta^j t^m \left[ (-1)^j \binom{j+t-1}{j+1} n + \sum_{k=1}^n \binom{k-t+1}{j+1} \right]$$

Thus,

**Proposition 1.5** (Double sums of powers via Newton's series). *For non-negative integers  $n, m$  and an arbitrary integer  $t$*

$$\Sigma^2 n^m = \sum_{j=0}^m \Delta^j t^m \left[ (-1)^j \binom{j+t-1}{j+1} n + (-1)^{j+1} \binom{j+t-1}{j+2} n^0 + \binom{n-t+2}{j+2} \right]$$

*Proof.* We have  $\Sigma^2 n^m = \sum_{j=0}^m \Delta^j t^m \left[ (-1)^j \binom{j+t-1}{j+1} n + \sum_{k=1}^n \binom{k-t+1}{j+1} \right]$ , where  $\sum_{k=1}^n \binom{k-t+1}{j+1} = (-1)^{j+1} \binom{j+t-1}{j+2} n^0 + \binom{n-t+2}{j+2}$  by means of segmented hockey stick identity (1.3).  $\square$

For example, by setting  $t = 5$ , the double sums of powers are

$$\begin{aligned} \Sigma^2 n^0 &= 1 \left( \binom{n-3}{2} + \binom{4}{1} n - \binom{4}{2} \right) \\ \Sigma^2 n^1 &= 5 \left( \binom{n-3}{2} + \binom{4}{1} n - \binom{4}{2} \right) + 1 \left( \binom{n-3}{3} - \binom{5}{2} n + \binom{5}{3} \right) \\ \Sigma^2 n^2 &= 25 \left( \binom{n-3}{2} + \binom{4}{1} n - \binom{4}{2} \right) + 11 \left( \binom{n-3}{3} - \binom{5}{2} n + \binom{5}{3} \right) \\ &\quad + 2 \left( \binom{n-3}{4} + \binom{6}{3} n - \binom{6}{4} \right) \\ \Sigma^2 n^3 &= 125 \left( \binom{n-3}{2} + \binom{4}{1} n - \binom{4}{2} \right) + 91 \left( \binom{n-3}{3} - \binom{5}{2} n + \binom{5}{3} \right) \\ &\quad + 36 \left( \binom{n-3}{4} + \binom{6}{3} n - \binom{6}{4} \right) + 6 \left( \binom{n-3}{5} - \binom{7}{4} n + \binom{7}{5} \right) \end{aligned}$$

The coefficients 1, 5, 1, 25, 11, 2, ... is the sequence [A391635](#) in the OEIS [7].

In general,

$$\Sigma^2 n^m = \sum_{j=0}^m \Delta^j 5^m \left[ \binom{n-3}{j+2} + (-1)^j \binom{j+4}{j+1} n^1 + (-1)^{j+1} \binom{j+4}{j+2} n^0 \right]$$

Similarly, we obtain the formula for the triple sums of powers

**Proposition 1.6** (Triple sums of powers via Newton's series). *For non-negative integers  $n, m$  and an arbitrary integer  $t$*

$$\begin{aligned} \Sigma^3 n^m = \sum_{j=0}^m \Delta^j t^m & \left[ (-1)^j \binom{j+t-1}{j+1} \Sigma^2 n^0 + (-1)^{j+1} \binom{j+t-1}{j+2} \Sigma^1 n^0 + \right. \\ & \left. + (-1)^{j+2} \binom{j+t-1}{j+3} \Sigma^0 n^0 + \binom{n-t+3}{j+3} \right] \end{aligned}$$

*Proof.* By summing up double sums of powers (1.5), we get

$$\begin{aligned} \Sigma^3 n^m &= \sum_{j=0}^m \Delta^j t^m \sum_{k=1}^n \left[ (-1)^j \binom{j+t-1}{j+1} k^1 + (-1)^{j+1} \binom{j+t-1}{j+2} k^0 + \binom{k-t+2}{j+2} \right] \\ &= \sum_{j=0}^m \Delta^j t^m \left[ (-1)^j \binom{j+t-1}{j+1} \sum_{k=1}^n k^1 + (-1)^{j+1} \binom{j+t-1}{j+2} \sum_{k=1}^n k^0 + \sum_{k=1}^n \binom{k-t+2}{j+2} \right] \end{aligned}$$

Note that  $\sum_{k=1}^n k^1 = \Sigma^2 n^0$  and  $\sum_{k=1}^n k^0 = \Sigma^1 n^0$ . Thus,

$$\sum_{k=1}^n \binom{k-t+2}{j+2} = (-1)^{j+2} \binom{j+t-1}{j+3} \Sigma^0 n^0 + \binom{n-t+3}{j+3}$$

by segmented hockey stick identity (1.3). This completes the proof.  $\square$

For example, by setting  $t = 4$ , the triple sums of powers are

$$\begin{aligned}\Sigma^3 n^0 &= 1 \left( \binom{n-1}{3} + \binom{3}{1} \Sigma^2 n^0 - \binom{3}{2} \Sigma^1 n^0 + \binom{3}{3} \Sigma^0 n^0 \right) \\ \Sigma^3 n^1 &= 4 \left( \binom{n-1}{3} + \binom{3}{1} \Sigma^2 n^0 - \binom{3}{2} \Sigma^1 n^0 + \binom{3}{3} \Sigma^0 n^0 \right) \\ &\quad + 1 \left( \binom{n-1}{4} - \binom{4}{2} \Sigma^2 n^0 + \binom{4}{3} \Sigma^1 n^0 - \binom{4}{4} \Sigma^0 n^0 \right) \\ \Sigma^3 n^2 &= 16 \left( \binom{n-1}{3} + \binom{3}{1} \Sigma^2 n^0 - \binom{3}{2} \Sigma^1 n^0 + \binom{3}{3} \Sigma^0 n^0 \right) \\ &\quad + 9 \left( \binom{n-1}{4} - \binom{4}{2} \Sigma^2 n^0 + \binom{4}{3} \Sigma^1 n^0 - \binom{4}{4} \Sigma^0 n^0 \right) \\ &\quad + 2 \left( \binom{n-1}{5} + \binom{5}{3} \Sigma^2 n^0 - \binom{5}{4} \Sigma^1 n^0 + \binom{5}{5} \Sigma^0 n^0 \right)\end{aligned}$$

In general,

$$\begin{aligned}\Sigma^3 n^m &= \sum_{j=0}^m \Delta^j 4^m \left[ (-1)^j \binom{j+3}{j+1} \Sigma^2 n^0 + (-1)^{j+1} \binom{j+3}{j+2} \Sigma^1 n^0 + \right. \\ &\quad \left. + (-1)^{j+2} \binom{j+3}{j+3} \Sigma^0 n^0 + \binom{n-1}{j+3} \right]\end{aligned}$$

Continuing similarly, we derive formula for multifold sums of powers, which is

**Theorem 1.7** (Multifold sums of powers via Newton's series). *For non-negative integers  $r, n, m$  and an arbitrary integer  $t$*

$$\Sigma^r n^m = \sum_{j=0}^m \Delta^j t^m \left[ \left( \sum_{s=1}^r (-1)^{j+s-1} \binom{j+t-1}{j+s} \Sigma^{r-s} n^0 \right) + \binom{n-t+r}{j+r} \right]$$

*Proof.* By Newton's series for power (1.2) and repeated applications of the segmented hockey stick identity (1.3). □

In its explicit form

**Example 1.8** (Explicit expansion of the  $s$ -sum in the  $r$ -fold case). *For non-negative integers  $r, n, m$  and an arbitrary integer  $t$ , the  $r$ -fold sum  $\Sigma^r n^m$  can be written as*

$$\begin{aligned} \Sigma^r n^m = \sum_{j=0}^m \Delta^j t^m & \left[ (-1)^j \binom{j+t-1}{j+1} \Sigma^{r-1} n^0 + (-1)^{j+1} \binom{j+t-1}{j+2} \Sigma^{r-2} n^0 \right. \\ & + (-1)^{j+2} \binom{j+t-1}{j+3} \Sigma^{r-3} n^0 + \dots + (-1)^{j+r-1} \binom{j+t-1}{j+r} \Sigma^0 n^0 \\ & \left. + \binom{n-t+r}{j+r} \right] \end{aligned}$$

We may observe that

**Proposition 1.9** (Multifold sum of zero powers). *For integers  $r$  and  $n$*

$$\Sigma^r n^0 = \binom{r+n-1}{r}$$

*Proof.* By hockey stick identity  $\sum_{k=0}^t \binom{j+k}{j} = \binom{j+t+1}{j+1}$ . □

Which yields the following binomial variations of the multifold sums of powers (1.7)

**Proposition 1.10** (Multifold sums of powers binomial form). *For non-negative integers  $r, n, m$  and an arbitrary integer  $t$*

$$\Sigma^r n^m = \sum_{j=0}^m \Delta^j t^m \left[ \left( \sum_{s=1}^r (-1)^{j+s-1} \binom{j+t-1}{j+s} \binom{r-s+n-1}{r-s} \right) + \binom{n-t+r}{j+r} \right]$$

**Proposition 1.11** (Multifold sums of powers binomial form re-indexed). *For non-negative integers  $r, n, m$  and an arbitrary integer  $t$*

$$\Sigma^r n^m = \sum_{j=0}^m \Delta^j t^m \left[ \left( \sum_{s=0}^{r-1} (-1)^{j+s} \binom{j+t-1}{j+s+1} \binom{r-s+n-2}{r-s-1} \right) + \binom{n-t+r}{j+r} \right]$$

Finite differences of powers are closely related to Stirling numbers of the second kind

**Lemma 1.12** (Finite differences via Stirling numbers). *For non-negative integers  $j, m$  and an arbitrary integer  $t$*

$$\Delta^j t^m = \sum_{k=0}^m \binom{t}{k} \left\{ \begin{matrix} m \\ j+k \end{matrix} \right\} (j+k)!$$



Which implies variations of the formulas for sums of powers

**Proposition 1.13** (Ordinary sums of powers via Stirling numbers). *For non-negative integers  $n, m$  and arbitrary integer  $t$*

$$\Sigma^1 n^m = \sum_{j=0}^m \sum_{k=0}^m \left[ (-1)^j \binom{j+t-1}{j+1} + \binom{n-t+1}{j+1} \right] \binom{t}{k} \left\{ \begin{matrix} m \\ j+k \end{matrix} \right\} (j+k)!$$

*Proof.* By ordinary sums of powers via Newton's series (1.4) and forward finite difference via Stirling numbers of the second kind (1.12).  $\square$

By setting  $t = 0$  into (1.13) yields well-known identity for sums of powers in terms of Stirling numbers

**Corollary 1.14.** *For non-negative integers  $n, m$*

$$\Sigma^1 n^m = \sum_{j=0}^m \binom{n+1}{j+1} \left\{ \begin{matrix} m \\ j \end{matrix} \right\} j!$$

In general,

**Proposition 1.15** (Multifold sums of powers via Stirling numbers). *For non-negative integers  $r, n, m$  and an arbitrary integer  $t$*

$$\Sigma^r n^m = \sum_{j=0}^m \sum_{k=0}^m \left[ \left( \sum_{s=1}^r (-1)^{j+s-1} \binom{j+t-1}{j+s} \Sigma^{r-s} n^0 \right) + \binom{n-t+r}{j+r} \right] \binom{t}{k} \left\{ \begin{matrix} m \\ j+k \end{matrix} \right\} (j+k)!$$

*Proof.* By multifold sums of powers via Newton's series (1.7) and forward finite difference via Stirling numbers of the second kind (1.12).  $\square$

The proposition above can be presented in a pure binomial form as well, by means of the identity (1.9):  $\Sigma^r n^0 = \binom{r+n-1}{r}$ .

In addition, we are able to express multifold sums of powers via Eulerian numbers, by expressing the forward finite difference via the Worpitzky identity [9]

**Lemma 1.16** (Worpitzky identity). *For non-negative integers  $t, m$*

$$t^m = \sum_{k=0}^m \binom{t+k}{m} \left\langle \begin{matrix} m \\ k \end{matrix} \right\rangle$$

where  $\langle n \rangle_k$  are Eulerian numbers. Thus,

**Lemma 1.17** (Finite difference via Eulerian numbers). *For non-negative integers  $j, m$  and an arbitrary integer  $t$*

$$\Delta^j t^m = \sum_{k=0}^m \binom{t+k}{m-j} \langle m \rangle_k$$

Therefore,

**Proposition 1.18** (Multifold sums of powers via Eulerian numbers). *For non-negative integers  $r, n, m$  and an arbitrary integer  $t$*

$$\Sigma^r n^m = \sum_{j=0}^m \sum_{k=0}^m \left[ \left( \sum_{s=1}^r (-1)^{j+s-1} \binom{j+t-1}{j+s} \Sigma^{r-s} n^0 \right) + \binom{n-t+r}{j+r} \right] \binom{t+k}{m-j} \langle m \rangle_k$$

*Proof.* By multifold sums of powers via Newton's series (1.7) and forward finite difference via Eulerian numbers (1.17).  $\square$

Which implies variations of the formulas for sums of powers

**Proposition 1.19** (Ordinary sums of powers via Eulerian numbers). *For non-negative integers  $n, m$  and an arbitrary integer  $t$*

$$\Sigma^1 n^m = \sum_{j=0}^m \sum_{k=0}^m \left[ (-1)^j \binom{j+t-1}{j+1} + \binom{n-t+1}{j+1} \right] \binom{t+k}{m-j} \langle m \rangle_k$$

By setting  $t = 0$  into (1.19) yields a well-known identity for sums of powers in terms of Eulerian numbers

**Corollary 1.20** (Sums of powers via Eulerian numbers in zero). *For non-negative integers  $n, m$*

$$\Sigma^1 n^m = \sum_{j=0}^m \sum_{k=0}^m \binom{n+1}{j+1} \binom{k}{m-j} \langle m \rangle_k$$

## 2. BACKWARD DIFFERENCE FORM

The formula for multifold sums of powers via Newton's series (1.7) can be expressed in terms of backward differences easily, because

**Proposition 2.1.** *For integers  $j, m, t$*

$$\Delta^j t^m = \nabla^j (t + j)^m$$

Thus,

**Proposition 2.2** (Multifold sums of powers via backward differences). *For non-negative integers  $r, n, m$  and an arbitrary integer  $t$*

$$\Sigma^r n^m = \sum_{j=0}^m \nabla^j (t + j)^m \left[ \left( \sum_{s=1}^r (-1)^{j+s-1} \binom{j+t-1}{j+s} \Sigma^{r-s} n^0 \right) + \binom{n-t+r}{j+r} \right]$$

*Proof.* By multifold sums of powers via Newton's series (1.7) and by proposition (2.1).  $\square$

## 3. CENTRAL DIFFERENCE FORM

The formula for multifold sums of powers via Newton's series (1.7) can be expressed in terms of central differences easily, because

**Proposition 3.1.** *For integers  $j, m, t$*

$$\Delta^j t^m = \delta^j \left( t + \frac{j}{2} \right)^m$$

Thus,

**Proposition 3.2** (Multifold sums of powers via central differences). *For non-negative integers  $r, n, m$  and an arbitrary integer  $t$*

$$\Sigma^r n^m = \sum_{j=0}^m \delta^j \left( t + \frac{j}{2} \right)^m \left[ \left( \sum_{s=1}^r (-1)^{j+s-1} \binom{j+t-1}{j+s} \Sigma^{r-s} n^0 \right) + \binom{n-t+r}{j+r} \right]$$

*Proof.* By multifold sums of powers via Newton's series (1.7) and by proposition (3.1).  $\square$

#### 4. FUTURE RESEARCH

In this manuscript we focus on the idea to combine Newton's interpolation formula for forward differences (1.2) and the hockey-stick family identities (e.g (1.3)) to express the sums of powers seamlessly.

This particular idea is great, however it can be generalized even further. Thus, the main idea is to utilize an interpolation formula for power  $n^m$  in terms of *abstract difference operator*  $D(n^m)$  and binomial coefficients  $\binom{f(n)}{k}$ .

We are not limited to linear difference operators  $\Delta, \nabla, \delta$ , there is a complete theory on dynamic differential equations on time-scales, founded by Bohner and Peterson [10]. For example, Jackson [11] derivative is given by

$$D_q(f(x)) = \frac{f(qx) - f(x)}{qx - x}$$

Thus, finding interpolation formula for  $f(x) = x^n$  in terms of  $D_q(f(x))$  implies new formulas for sums of powers.

In general, let be an abstract interpolation formula for powers

$$n^m = \sum_k \binom{f(n)}{k} D(n^m, k)$$

Thus, the formula of sums of powers involves the abstract difference operator  $D$  evaluated at some point  $k$  and the hockey-stick family identity over the binomial coefficients  $\binom{n}{k}$

$$\Sigma^1 n^m = \sum_k D(n^m, k) \sum_{j \leq n} \binom{f(j)}{k}$$

Similarly, for multifold sums of powers

$$\Sigma^r n^m = \sum_k D(n^m, k) \binom{f(n+r)}{k}$$

Many interpolation approaches involve rising factorials  $x^{(n)}$ , falling factorials  $(x)_n$ , or regular factorials  $n!$ , and thus can be expressed in terms of binomial coefficients, because

$$\frac{(x)_n}{n!} = \binom{x}{n}; \quad \frac{x^{(n)}}{n!} = \binom{x+n-1}{n}; \quad x^{[n]} = n \left(x + \frac{n}{2} - 1\right)_{n-1}$$

In particular, Donald Knuth provides the formula for multifold sums of odd powers [3] based on operator of central finite differences evaluated in zero, and Newton's interpolation formula for central differences [2]

**Proposition 4.1** (Multifold sums of odd powers).

$$\begin{aligned} \Sigma^r n^{2m-1} &= \sum_{k=1}^m \binom{n+k-1+r}{2k-1+r} \frac{1}{2k} \delta^{2k} 0^{2m} \\ &= \sum_{k=1}^m \binom{n+k-1+r}{2k-1+r} (2k-1)! T(2m, 2k) \end{aligned}$$

where  $T(n, k)$  are the central factorial numbers of the second kind, see [12, section 58] and [13, formula (10a)]

$$T(n, k) = \frac{1}{k!} \delta^k 0^n = \frac{1}{k!} \sum_{j=0}^k (-1)^j \binom{k}{j} \left(\frac{k}{2} - j\right)^n$$

Central factorial numbers of the second kind  $T(n, k)$  were defined by Riordan in [14, ch. 6.5, formula (24)] by polynomial identity

**Lemma 4.2** (Riordan power identity).

$$n^m = \sum_{k=1}^m T(m, k) n^{[k]}$$

where  $n^{[k]}$  are central factorials  $n^{[k]} = n \prod_{j=0}^{k-1} \left(n + \frac{k}{2} - j\right)$ .

The sequence A008957 in the OEIS [7] provides non-zero central factorial numbers of the second kind  $T(2n, 2k)$ .

As future research direction, the Knuth's formula (4.1) utilizes the operator of central finite differences evaluated in zero. Thus, it is worth to investigate the existence of sums of odd powers involving the central differences evaluated at an arbitrary integer point  $t$ , similar to multifold sums of powers via Newton's series for central differences.

## CONCLUSIONS

In this manuscript we have derived formulas for multifold sums of powers by utilizing Newton's interpolation formula. Furthermore, we provide formulas for multifold sums of powers in terms of Stirling numbers of the second kind, and Eulerian numbers. In addition, in (4) we discuss the future research directions that may lead to a complete framework for sums of powers, by means of combining interpolation approaches, binomial coefficients and variations of the hockey-stick identity for binomial coefficients. The most important results of this manuscript are validated using Mathematica programs, see (5).

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## PROOF OF SEGMENTED HOCKEY STICK IDENTITY

First we split the sum  $\sum_{k=0}^n \binom{-t+k}{j}$  into two sub-sums so that we discuss them separately

$$\sum_{k=0}^n \binom{-t+k}{j} = \sum_{k=0}^{t-1} \binom{-t+k}{j} + \sum_{k=t}^n \binom{-t+k}{j}$$

We assume that the two sums above run over the partition  $\{0, 1, 2, \dots, t, \dots, n\}$ , with  $t < n$ .

Considering the sum  $\sum_{k=0}^{t-1} \binom{-t+k}{j}$  we notice that

$$\begin{aligned} \sum_{k=0}^{t-1} \binom{-t+k}{j} &= \binom{-t}{j} + \binom{-t+1}{j} + \binom{-t+2}{j} + \dots + \\ &\quad + \binom{-t+t-2}{j} + \binom{-t+t-1}{j} \end{aligned}$$

Thus

$$\sum_{k=0}^{t-1} \binom{-t+k}{j} = \sum_{k=1}^t \binom{-k}{j} = \sum_{k=0}^{t-1} \binom{-k-1}{j}$$

By using the identity  $\binom{-k}{j} = (-1)^j \binom{j+k-1}{j}$ , we obtain

$$\binom{-k-1}{j} = \binom{-(k+1)}{j} = (-1)^j \binom{j+k}{j}$$

Thus

$$\sum_{k=0}^{t-1} \binom{-t+k}{j} = (-1)^j \sum_{k=0}^{t-1} \binom{j+k}{j} = (-1)^j \binom{j+t}{j+1}$$

by the hockey-stick identity  $\sum_{k=0}^t \binom{j+k}{j} = \binom{j+t+1}{j+1}$ .

Considering the sum  $\sum_{k=t}^n \binom{-t+k}{j}$  we notice that

$$\sum_{k=t}^n \binom{-t+k}{j} = \sum_{k=0}^{n-t} \binom{k}{j}$$

Thus

$$\sum_{k=t}^n \binom{-t+k}{j} = \sum_{k=0}^{n-t} \binom{k}{j} = \binom{n-t+1}{j+1}$$

again by the hockey-stick identity  $\sum_{k=0}^t \binom{j+k}{j} = \binom{j+t+1}{j+1}$ . Combining the two parts, we obtain

$$\sum_{k=0}^n \binom{-t+k}{j} = (-1)^j \binom{j+t}{j+1} + \binom{n-t+1}{j+1}$$

This completes the proof.

## 5. MATHEMATICA PROGRAMS

Use the *Mathematica* package [16] to validate the results

Mathematica Function	Validates / Prints
MultifoldSumOfPowersRecurrence[r, n, m]	Computes $\sum^r n^m$
ValidateOrdinarySumsOfPowersViaNewtonsSeries[5]	Validates Proposition (1.4)
ValidateDoubleSumsOfPowersViaNewtonsSeries[5]	Validates Proposition (1.5)
ValidateMultifoldSumsOfPowersViaNewtonsSeries[5]	Validates Theorem (1.7)
ValidateFiniteDifferenceViaStirlingNumbers[t]	Validates Lemma (1.12)
ValidateFiniteDifferenceViaEulerianNumbers[t]	Validates Lemma (1.17)
ValidateMultifoldSumsOfPowersViaCentralDifferences[r]	Validates Proposition (3.2)
ValidateMultifoldSumsOfPowersViaBackwardDifferences[r]	Validates Proposition (2.2)
ValidateMultifoldSumsOfPowersViaStirlingNumbers[r]	Validates Proposition (1.15)
ValidateMultifoldSumsOfPowersViaEulerianNumbers[r]	Validates Proposition (1.18)
ValidateMultifoldSumsOfPowersBinomialForm[r]	Validates Proposition (1.10)
ValidateMultifoldSumsOfPowersBinomialFormReindexed[r]	Validates Proposition (1.11)

DEVOPS ENGINEER

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