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Regular Sequences of Symmetric Polynomials

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ABSTRACT - A set of n homogeneous polynomials in n variables is a regular sequence if the associated polynomial system has only the obvious solution $(0, 0, \ldots, 0)$. Denote by $p_k(n)$ the power sum symmetric polynomial in n variables $x_1^k + x_2^k + \ldots + x_n^k$. The interpretation of the q-analogue of the binomial coefficient as Hilbert function leads us to discover that n consecutive power sums in n variables form a regular sequence. We consider then the following problem: describe the subsets $A \subset \mathbb{N}^*$ of cardinality n such that the set of polynomials $p_a(n)$ with $a \in A$ is a regular sequence. We prove that a necessary condition is that $n!$ divides the product of the elements of A. To find an easily verifiable sufficient condition turns out to be surprisingly difficult already for $n = 3$. Given positive integers $a < b < c$ with $\gcd(a, b, c) = 1$, we conjecture that $p_a(3), p_b(3), p_c(3)$ is a regular sequence if and only if $abc \equiv 0 \pmod 6$. We provide evidence for the conjecture by proving it in several special instances.

1. Introduction.

For $d, n \in \mathbb{N}$ let $P_{d,n}(q)$ be the q-analogue of the binomial coefficient (also called Gaussian polynomial)

$$P_{d,n}(q) := \begin{bmatrix} n+d \\ n \end{bmatrix}_q = \frac{[n+d]_q!}{[n]_q!\,[d]_q!} \tag{1.1}$$

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where

$$[j]_q! = \prod_{i=1}^{j} \frac{1-q^i}{1-q} = \prod_{i=1}^{j} (1+q+\ldots+q^{i-1}).$$

It is well known that $P_{d,n}(q) \in \mathbb{Z}[q]$. Furthermore for a finite field F, $P_{d,n}(q)$ evaluated at $q = |F|$ gives exactly the number of F-subspaces of F^{n+d} of dimension n, [S, 1.3.18]. It is also known that the coefficient of q^k in $P_{d,n}(q)$ is the number of partitions of k with at most n parts and parts bounded by d, [S, 1.3.19]. This interpretation leads to the following construction. Consider the polynomial ring $R = \mathbb{C}[x_1, x_2, \ldots, x_n]$ with the usual action of the permutation group $G = S_n$. The monomial complete intersection $I = (x_1^{d+1}, x_2^{d+1}, \ldots, x_n^{d+1})$ is fixed by G, so that G acts as well on the quotient ring $A = R/I$. The homogeneous part A_k of degree k of A has a $\mathbb{C}$-basis consisting of the monomials in $x_1^{a_1} x_2^{a_2} \cdots x_n^{a_n}$ with $a_1 + a_2 + \ldots + a_n = k$ and $a_i \leq d$ for all i. For a partition $\lambda : \lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n$ denote by m_λ the monomial symmetric polynomial

$$m_\lambda = x_1^{\lambda_1} x_2^{\lambda_2} \cdots x_n^{\lambda_n} + \text{symmetric terms},$$

where "symmetric terms" means the sum of all terms that have to be added to complete the monomial $x_1^{\lambda_1} x_2^{\lambda_2} \cdots x_n^{\lambda_n}$ to a symmetric polynomial in $x_1, x_2, \ldots, x_n$. The invariant ring A^G in degree k has a $\mathbb{C}$-basis consisting of the elements m_λ where λ is a partition of k in at most n parts with parts smaller than $d+1$. In other words, $P_{d,n}(q)$ is the Hilbert series of A^G. In characteristic 0 the extraction of the invariant submodule is an exact functor. So we have $A^G = R^G/I^G$, where $R^G = \mathbb{C}[e_1, e_2, \ldots, e_n]$ and e_i is the elementary symmetric polynomial of degree i. Since the e_i's are algebraically independent, the Hilbert series of R^G is $1/\prod_{i=1}^{n}(1-q^i)$. Since we know that $P_{d,n}(q)$ is the Hilbert series of A^G, we see that A^G has the Hilbert series of a complete intersection in R^G defined by elements of degree $d+1, d+2, \ldots, d+n$. These considerations suggest that the ideal $I^G = I \cap R^G$ might be generated by

$$p_{d+1}, p_{d+2}, \ldots, p_{d+n}$$

where $p_i = x_1^i + x_2^i + \cdots + x_n^i$ is the power sum of degree i and that they form a regular sequence. Since the inclusion $(p_{d+1}, p_{d+2}, \ldots, p_{d+n}) \subseteq I^G$ is obvious, to prove the equality it is enough to prove that $p_{d+1}, p_{d+2}, \ldots, p_{d+n}$ form a regular sequence in R^G or, which is the same, in R. We will see that this is indeed the case, see Proposition 2.9. We give two (simple) proofs of Proposition 2.9; one is based on Newton's relations and the other on

Vandermonde's determinant. Denote by h_i the complete symmetric polynomial of degree i, that is, the sum of all the monomials of degree i in $x_1, \dots, x_n$. More generally, we are led to consider regular sequences of symmetric polynomials. In particular regular sequences of power sums p_i and regular sequences of complete symmetric polynomials h_i. Even for $n = 3$ these questions turn out to be difficult. For indices a, b, c with $\gcd(a, b, c) = 1$ we conjecture that p_a, p_b and p_c form a regular sequence exactly when $6 \mid abc$. We are able to verify this conjecture in a few cases in which the property under investigation is translated into the non-vanishing of a rational number which appears as a coefficient in the relevant expressions or on the irreducibility over the rationals of certain polynomials obtained by elimination, see Theorem 2.11, Proposition 2.13 and Remark 2.14. Other interesting algebraic aspects of ideals and algebras of power sums are investigated by Lascoux and Pragacz [LP] and by Dvornicich and Zannier [DZ]. We thank Riccardo Biagioli, Francesco Brenti, Alain Lascoux and Michael Filaseta for useful suggestions and comments.

2. Regular sequences of symmetric polynomials

Set $R_n = \mathbb{C}[x_1, x_2, \dots, x_n]$. Following Macdonald, we denote by $e_k(n)$, $p_k(n)$ and $h_k(n)$ the elementary symmetric polynomial, the power sum and the complete symmetric polynomial of degree k in n-variables, respectively. When n is clear from the context or irrelevant we will simply denote them by e_k, p_k and h_k, respectively. For a subset $A \subset \mathbb{N}^*$ we set

$$p_A(n) = \{p_a(n) : a \in A\} \quad \text{and} \quad h_A(n) = \{h_a(n) : a \in A\}.$$

Question 2.1. *For which subsets $A \subset \mathbb{N}^*$ with $|A| = n$ is the set of polynomials $p_A(n)$ (respectively $h_A(n)$) a regular sequence in R_n? That is, when is $(0, \dots, 0)$ the only common zero of the equations $p_a(n) = 0$ (respectively $h_a(n) = 0$), $a \in A$?*

In the following we list several auxiliary observations.

Lemma 2.2. *Let $A \subset \mathbb{N}^*$ with $|A| = n$. Set $d = \gcd(A)$ and $A' = \{a/d : a \in A\}$. Then $p_A(n)$ is a regular sequence if and only if $p_{A'}(n)$ is a regular sequence.*

Proof. Note that if $(z_1, z_2, \dots, z_n)$ is a common zero of the $p_a(n)$'s with $a \in A$ then $(z_1^d, z_2^d, \dots, z_n^d)$ is a common zero of the $p_a(n)$'s with $a \in A'$

and that if $(z_1, z_2, \ldots, z_n)$ is a common zero of the $p_a(n)$'s with $a \in A'$ then $(z_1^{1/d}, z_2^{1/d}, \ldots, z_n^{1/d})$ is a common zero of the $p_a(n)$'s with $a \in A$ where $z_i^{1/d}$ denotes any d-th root of z_i. □

REMARK 2.3. For a set A of cardinality n the condition that $p_A(n)$ is a regular sequence can be rephrased in terms of a resultant: the resultant of the set must be non-zero. More directly, one can express the same fact by imposing the condition that the ideal generated by $p_A(n)$ contains all the forms of degree

$$\left(\sum_{a \in A} a\right) - n + 1.$$

This boils down to the evaluation of the rank of a $\{0,1\}$-matrix of large size. However, we have not been able to compute the resultant or to evaluate the rank of the matrix efficiently.

LEMMA 2.4. *Let $A \subset \mathbb{N}^*$ with $|A| = n$. Set $d = \gcd(A)$ and $A' = \{a/d : a \in A\}$. Then we have:*

(a) *The equations $p_a(2) = 0$, $a \in A$, have a non-trivial common zero in $\mathbb{C}^2$ if and only if the elements in A' are all odd.*

(b) *The equations $h_a(2) = 0$, $a \in A$, have a non-trivial common zero in $\mathbb{C}^2$ if and only if* $\gcd(\{a+1 : a \in A\}) = 1$.

PROOF. (a) As in the proof of the lemma above, the polynomials $p_a(2)$ with $a \in A$ have a non-trivial common zero if and only if the polynomials $p_a(2)$ with $a \in A'$ have a non-trivial common zero. So we may assume that $A = A'$. If all the elements of A are odd then $(1, -1)$ is a non-trivial common zero. Conversely, if there is a non-trivial common zero, then we may assume this zero to be $(x, 1)$. In this case, we have $x^a = -1$ for all $a \in A$. Since $\gcd(A) = 1$ we can find a linear combination of the elements in $A = \{a_1, a_2, \ldots, a_n\}$ of the type $\sum j_k a_k = 1$ with $j_k \in \mathbb{Z}$. Hence we have $x^{j_k a_k} = (-1)^{j_k}$ and thus $x = (-1)^{\sum j_k}$. Therefore we have either $x = 1$, which is impossible, or $x = -1$ which implies that all the elements of A are odd.

(b) Denote by (*) the condition: the equations $h_a(2) = 0$ with $a \in A$ have a non-trivial common zero in $\mathbb{C}^2$. So (*) holds if and only if the equations have a common zero of type $(c, 1)$. Obviously $c \neq 1$, so we can multiply each $h_a(2)$ by $c - 1$. We obtain that (*) holds if and only if the equations $x^{a+1} - 1 = 0$ with $a \in A$ have a common root $\neq 1$. In other words,

$\gcd(\{x^{a+1}-1 : a \in A\}) \neq x-1$. But $\gcd(\{x^{a+1}-1 : a \in A\}) = x^t - 1$ with $t = \gcd(\{a+1 : a \in A\})$, and we obtain the desired characterization. □

This answers Question 2.1 for $n = 2$. Namely, Lemma 2.4 implies the following fact.

LEMMA 2.5. *Let $a, b \in \mathbb{N} \setminus \{0\}$ and $d = \gcd(a, b)$. Then we have:*

(1) *$(p_a(2), p_b(2))$ is a regular sequence if and only if a/d or b/d is even.*

(2) *$(h_a(2), h_b(2))$ is a regular sequence if and only if $\gcd(a+1, b+1) = 1$.*

Here is another fact.

LEMMA 2.6.

(1) *If $a \not\equiv 0 \pmod{c}$ and u is a primitive c-th root of unity then*

$$(1, u, u^2, \dots, u^{c-1}, 0, \dots, 0) \in \mathbb{C}^n$$

is a zero of $p_a(n)$ in $\mathbb{C}^n$ for all $n \geq c$.

(2) *Let $A \subset \mathbb{N}^*$ with $|A| = n$ and $1 \leq c \leq n$. Set $\beta_c = |\{a \in A : a \equiv 0 \pmod{c}\}|$. If $\beta_c < \lfloor n/c \rfloor$ then $p_A(n)$ is not a regular sequence. Here $\lfloor x \rfloor = \max\{m \in \mathbb{Z} : m \leq x\}$ is the standard floor function.*

PROOF. (1) Evaluating $p_a(n)$ at $(1, u, u^2, \dots, u^{c-1}, 0, \dots, 0)$ yields $\sum_{i=1}^{c} u^{(i-1)a}$. Multiplying the sum by $u^a - 1$, we obtain $u^{ca} - 1$ which is 0. Since u is a primitive c-th root of unity and $a \not\equiv 0 \pmod{c}$, we have $u^a - 1 \neq 0$. It follows that $\sum_{i=1}^{c} u^{(i-1)a} = 0$.

(2) Write $n = qc + r$ with $0 \leq r < c$ so that $q = \lfloor n/c \rfloor$. Let u be a primitive c-th root of unity. Let $(y_1, y_2, \dots, y_q) \in \mathbb{C}^q$ and consider the element $\tilde{y} \in \mathbb{C}^n$ obtained by concatenating $y_i(1, u, \dots, u^{c-1})$ for $i = 1, 2, \dots, q$ and by adding the zero vector of length r at the end. By (1) we know that every such $\tilde{y}$ is a zero of the $p_a(n)$'s with $a \not\equiv 0 \pmod{c}$. If we also impose that $\tilde{y}$ is a zero of the $p_a(n)$'s with $a \in A$ and $a \equiv 0 \pmod{c}$ we obtain β_c homogeneous equations in q variables. If $\beta_c < q$ then there exists a non-zero common solution to that system of equations. □

We list another auxiliary result.

LEMMA 2.7.

(1) *Let* $c > 2$ *and* $a + 2 \equiv 0$ *or* $1 \pmod{c}$*. Let* u_1, u_2, u_3 *be distinct* c*-th roots of unity. Then* $p = (u_1, u_2, u_3, 0, \dots, 0) \in \mathbb{C}^n$ *is a zero of* $h_a(n)$ *in* $\mathbb{C}^n$ *for all* $n \geq 3$*.*

(2) *Let* $A \subset \mathbb{N}^*$ *with* $|A| = n$ *and* $2 < c$*. Assume that for all* $a \in A$ *one has* $a + 2 \equiv 0$ *or* $1 \pmod{c}$*. Then* $h_A(n)$ *is not a regular sequence.*

PROOF. (1) We may assume $n = 3$. To show that $h_a(3)$ evaluated at $p = (u_1, u_2, u_3)$ is 0 we first multiply $h_a(3)$ with $\Delta = (x_1 - x_2)\,(x_1 - x_3)\,(x_2 - x_3)$. A simple calculation shows that

$$h_a(3)\Delta = x_1^{a+2}(x_2 - x_3) + x_2^{a+2}(x_3 - x_1) + x_3^{a+2}(x_1 - x_2).$$

Since, by assumption, we have $u_i^{a+2} = 1$ or $u_i^{a+2} = u_i$ for all i, this expression vanishes at p.

(2) It follows immediately from (1) that p is a common zero of the equations $h_a(n)$. So $h_A(n)$ is not a regular sequence. □

For the general case of n homogeneous symmetric polynomials in R_n, there holds the following criterion.

LEMMA 2.8. *Let* $f_1, f_2, \dots, f_n$ *be a regular sequence of homogeneous symmetric polynomials in* R_n*. Then* $n!$ *divides* $(\deg f_1)(\deg f_2) \cdots (\deg f_n)$*.*

PROOF. For obvious reasons, $f_1, f_2, \dots, f_n$ is also a regular sequence in the ring of symmetric polynomials $\mathbb{C}[e_1, e_2, \dots, e_n]$. Then the Hilbert series of

$$\mathbb{C}[e_1, e_2, \dots, e_n]/(f_1, f_2, \dots, f_n)$$

is $\prod_{i=1}^{n} (1 - q^{\deg f_i})/(1 - q^i)$, and it must be a polynomial with integral coefficients. If we take the limit $q \to 1$, we obtain $\left(\prod_{i=1}^{n} \deg f_i\right)/n!$, which must be an integer. □

Next we prove that power sums, respectively complete symmetric polynomials, with consecutive indices form regular sequences.

PROPOSITION 2.9. *Let* $A \subset \mathbb{N}^*$ *be a set of* n *consecutive elements. Then both* $p_A(n)$ *and* $h_A(n)$ *are regular sequences in* R_n*.*

PROOF. We present two proofs for power sums and (sketch) two proofs for complete symmetric polynomials. Let a be the minimum of A. We first prove the assertion for the power sums.

Proof (1) for power sums: We argue by induction on a and n. If $n=1$ then the assertion is obvious. If $a=1$, then any common zero of $p_1, p_2, \ldots, p_n$ is also a common zero of $e_1, e_2, \ldots, e_n$ because $p_1, p_2, \ldots, p_n$ also generate the algebra of symmetric polynomials. But, obviously, the only common zero of the elementary symmetric polynomials is $(0, \ldots, 0)$. Now assume $n>1$ and $a>1$. For all $h \in \mathbb{N}$ we have Newton's identity

$$\sum_{k=0}^{n} (-1)^k e_{n-k}\, p_{k+h} = 0,$$

with the convention that $p_0 = n$ and $e_0 = 1$. For $h = a-1$ we have

$$e_n p_{a-1} = \sum_{k=1}^{n} (-1)^{k+1} e_{n-k}\, p_{k+a-1}.$$

If $z = (z_1, z_2, \ldots, z_n)$ is a common zero of $p_a, p_{a+1}, \ldots, p_{a+n-1}$ then it is also a zero of $e_n p_{a-1}$. So z is either a zero of p_{a-1}, and we conclude by induction on a that $z = (0, \ldots, 0)$ or z is a zero of e_n. In the second case, one of the coordinates of z is 0 and we conclude by induction on n that $z = (0, \ldots, 0)$.

Proof (2) for power sums: Let $z = (z_1, z_2, \ldots, z_n) \in \mathbb{C}^n$ be a solution of the polynomial system associated to $p_A(n)$. We have to prove that $z = 0$. Let c be the cardinality of the set $\{z_i : i = 1, \ldots, n\}$. We may assume that $z_1, z_2, \ldots, z_c$ are the distinct values among $z_1, z_2, \ldots, z_n$, and for $i = 1, \ldots, c$ set $m_i = |\{j : z_j = z_i\}|$, so that $m_i > 0$. Hence $p_k(z_1, \ldots, z_n) = m_1 z_1^k + \ldots + m_c z_c^k$. By assumption, $p_{a+j}(z_1, \ldots, z_n) = 0$ for $j = 0, \ldots, n-1$. Let V be the Vandermonde matrix (z_j^i) with $i = 0, \ldots, c-1$ and $j = 1, \ldots, c$. By construction, $\det V \neq 0$ and the column vector $(m_1 z_1^a, m_2 z_2^a, \ldots, m_c z_c^a)$ is in the kernel of V. It follows that $(m_1 z_1^a, m_2 z_2^a, \ldots, m_c z_c^a) = 0$, that is, $c = 1$ and $z_1 = 0$. This shows that $z = 0$.

Proof (1) works also for complete symmetric polynomials by replacing Newton's identity with the corresponding identity for the complete symmetric polynomials. For a second proof for complete symmetric polynomials, one observes that the initial ideal with respect to any term order with $x_1 > x_2 > \ldots > x_n$ of the ideal generated by $h_a(n), h_{a+1}(n), \ldots, h_{a+n-1}(n)$ contains (and hence is equal to) $(x_1^a, x_2^{a+1}, \ldots, x_n^{a+n-1})$. □

The above results (and many computer calculations) suggest the following conjecture.

CONJECTURE 2.10. *Let* $A = \{a, b, c\}$, *where* a, b, c *are positive integers with* $a < b < c$ *and* $\gcd(A) = 1$. *Then* $p_A(3)$ *is a regular sequence in* R_3 *if and only if* $abc \equiv 0 \pmod 6$.

The "only if" part has been proved in Lemma 2.8. In direction of the "if" part, we are able to offer the following partial result.

THEOREM 2.11. *Conjecture* 2.10 *is true if* A *either contains* 1 *and* n *with* $2 \leq n \leq 7$, *or if it contains* 2 *and* 3.

PROOF. For simplicity, let us denote by p_k and e_k the corresponding symmetric polynomials in 3 variables. In the following considerations we will use the basic fact that e_1, e_2, e_3 are algebraically independent generators for the algebra of symmetric polynomials in x_1, x_2, x_3.

Assume first that $A = \{1, n, m\}$ with $2 \leq n \leq 7$, $m \neq n$, and $6 \mid nm$. Formulas expressing the power sum p_h in terms of the elementary symmetric polynomials are well-known, see [M, Ex. 20, p. 33]. We will use the fact that every monomial $e_1^{\beta_1} e_2^{\beta_2} e_3^{\beta_3}$ with $\beta_1 + 2\beta_2 + 3\beta_3 = h$ appears in the expression of p_h with a non-zero coefficient. The cases $n = 2, 3, 4, 5, 7$ are easy since in those cases p_n is a monomial in e_2 and e_3 mod (e_1). For instance, $p_4 = u e_2^2$ mod (e_1) and $p_5 = u e_2 e_3$ mod (e_1), where u stands for a non-zero integer. This is enough to show that

$$\sqrt{(p_1, p_n)} = \begin{cases} \sqrt{(e_1, e_2)} & \text{if } n = 2, 4, \\ \sqrt{(e_1, e_3)} & \text{if } n = 3, \\ \sqrt{(e_1, e_2 e_3)} & \text{if } n = 5, 7, \end{cases}$$

where $\sqrt{I}$ denotes the radical of the ideal I. In the cases $n = 2$ or $n = 4$, we have $m = 3v$, hence $p_m = u e_3^v$ mod (e_1, e_2) for some non-zero integer u. This implies that $\sqrt{(p_1, p_n, p_m)} = \sqrt{(e_1, e_2, e_3)}$. One concludes in a similar manner in the cases $n = 3$ and $n = 5, 7$.

The proof for $n = 6$ is more complicated since p_6 is not a monomial mod (e_1). Indeed, $p_6 = -2e_2^3 + 3e_3^2$ mod (e_1). However, reducing p_m mod (e_1) and p_6, that is, replacing e_1 with 0 and e_3^2 with $(2/3)e_2^3$ we obtain

$$p_m = \begin{cases} a_m e_2^h \mod (p_1, p_6) & \text{if } m = 2h, \\ a_m e_2^{h-1} e_3 \mod (p_1, p_6) & \text{if } m = 2h + 1, \end{cases}$$

where a_m is an integer. The assertion that we have to prove is equivalent to the non-vanishing of coefficient a_m. The integer a_m can be computed using the formula expressing p_m in terms of the e_i's, see [M, Ex. 20, p. 33]. Explicitly, we have

$$a_m = \begin{cases} m \displaystyle\sum_{b=0}^{\lfloor h/3 \rfloor} \frac{(-1)^{h-b}}{h-b} \binom{h-b}{2b} (2/3)^b & \text{if } m = 2h, \\ -m \displaystyle\sum_{b=0}^{\lfloor h/3 \rfloor} \frac{(-1)^{h-b}}{h-b} \binom{h-b}{2b+1} (2/3)^b & \text{if } m = 2h+1. \end{cases}$$

To show that $a_m \neq 0$ for $m \neq 1$ and 6, we consider

$$f_m(x) = \begin{cases} m \displaystyle\sum_{b=0}^{\lfloor h/3 \rfloor} \frac{(-1)^{h-b}}{h-b} \binom{h-b}{2b} x^b & \text{if } m = 2h, \\ -m \displaystyle\sum_{b=0}^{\lfloor h/3 \rfloor} \frac{(-1)^{h-b}}{h-b} \binom{h-b}{2b+1} x^b & \text{if } m = 2h+1. \end{cases}$$

Since

$$\frac{2h}{h-b} \binom{h-b}{2b} = 2\binom{h-b}{2b} - \binom{h-b-1}{2b-1}$$

and

$$\frac{2h+1}{h-b} \binom{h-b}{2b+1} = 2\binom{h-b}{2b+1} - \binom{h-b-1}{2b},$$

the polynomials $f_m(x)$ are in $\mathbb{Z}[x]$. We have to show that $2/3$ is not a root of $f_m(x)$ for $m \neq 1, 6$. If $m < 8$, then $f_m(x)$ is a non-zero constant. So we may assume $m \geq 8$. If m is odd, then the coefficient of the term of degree 0 in $f_m(x)$ is odd. If m is even and $m \not\equiv 0 \pmod 6$ and $m \not\equiv 10 \pmod{18}$ then the leading coefficient of of $f_m(x)$ is not divisible by 3. This is enough to conclude that $2/3$ is not a root of $f_m(x)$ in this case. If $m \equiv 0 \pmod 6$ or $m \equiv 10 \pmod{18}$ one needs a more sophisticated analysis of the 3-adic valuation of the other coefficients of $f_m(x)$. The argument is given in the appendix.

Finally, assume that A contains 2 and 3, say $A = \{2, 3, d\}$ for some $d > 3$. Since p_1, p_2, p_3 generates the algebra of symmetric polynomials in x_1, x_2, x_3, we have $p_d = c_d p_1^d \bmod (p_2, p_3)$ for a uniquely determined rational number c_d. The statement we have to prove is equivalent to the non-vanishing of c_d. Since $e_2 = \frac{1}{2} p_1^2$ and $e_3 = \frac{1}{6} p_1^3 \bmod (p_2, p_3)$, from Newton's equation $p_d = e_1 p_{d-1} - e_2 p_{d-2} + e_3 p_{d-3}$ we obtain that

$$c_d = c_{d-1} - \frac{1}{2} c_{d-2} + \frac{1}{6} c_{d-3} \text{ for } d > 3, \text{ with } c_1 = 1, c_2 = 0, c_3 = 0.$$

Solving the linear recurrence, see [S, 4.1.1], we get that

$$c_d = \alpha^d + \beta^d + \bar{\beta}^d,$$

where $\alpha \in \mathbb{R}$, $0 < \alpha < 1$, and $\beta, \bar{\beta} \in \mathbb{C}$ are the roots of the polynomial

$$x^3 - x^2 + \frac{1}{2} x - \frac{1}{6} = 0.$$

We show that $c_d > 0$ for $d > 3$. To this end, it is enough to show that $\alpha^d > 2|\beta|^d$ for $d > 3$, equivalently, $(\alpha/|\beta|)^d > 2$. Hence it is enough to prove the statement for $d = 4$. With the help of a computer algebra program, we find that $(\alpha/|\beta|)^4 = 2.17\ldots$. □

In order to generalize part of Theorem 2.11 we need the following lemma.

Lemma 2.12. *Let* $A = \{a, b, c\}$, *where* $\gcd(A) = 1$ *and* $abc \equiv 0 \pmod 3$. *Then the zero-set of the polynomial system associated to* $p_A(3)$ *intersects* $\{(z_1, z_2, z_3) \in \mathbb{C}^3 : |z_1| = |z_2| = |z_3|\}$ *only in* $(0, 0, 0)$.

Proof. By contradiction, assume $(z_1, z_2, z_3) \in \mathbb{C}^3$ is a solution of the polynomial system associated to $p_A(3)$ and $|z_1| = |z_2| = |z_3| \neq 0$. Dividing by z_3, we may assume that $z_3 = 1$ and $|z_1| = |z_2| = 1$. Note that the only complex numbers w_1, w_2 satisfying $|w_1| = |w_2| = 1$ and $w_1 + w_2 + 1 = 0$ are the two primitive third roots of unity. Hence z_1^a, z_1^b and z_1^c are primitive third roots of 1. Since $\gcd(a, b, c) = 1$, there exist integers α, β, γ such that $a\alpha + b\beta + c\gamma = 1$. It follows that $z_1 = z_1^{a\alpha+b\beta+c\gamma} = (z_1^a)^\alpha (z_1^b)^\beta (z_1^c)^\gamma$ and hence z_1 itself is a third root of 1. But one among a, b, c, say a, is divisible by 3. Hence $z_1^a = 1$ which is a contradiction. □

We can now state, and prove, the announced partial generalization of Theorem 2.11.

Proposition 2.13. *Conjecture* 2.10 *holds if* A *contains* a *and* at *with* $t \in \{2, 3, 4, 5, 7\}$.

Proof. Let ρ be a primitive third root of 1. We claim that for $t \in \{2, 3, 4, 5, 7\}$ the zero-set of $p_1(3)$ and $p_t(3)$ consists (up to multiples and permutations) of at most $(1, \rho, \rho^2)$ (if $t \not\equiv 0 \bmod 3$)) and $(1, -1, 0)$ (if t is odd). The assertion follows from the fact that, for these values of t, $p_t(3)$ is a monomial in $e_2(3)$ and $e_3(3)$ mod $(e_1(3))$. From Lemma 2.5 it follows that every non-zero point $z = (z_1, z_2, z_3) \in \mathbb{C}^3$ in the zero set of $p_A(3)$ satisfies $z_1 z_2 z_3 \neq 0$. Hence, according to the claim above, (z_1^a, z_2^a, z_3^a) equals $(1, \rho, \rho^2)$ (up to multiples and permutations). Hence $|z_1| = |z_2| = |z_3|$ and this contradicts Lemma 2.12. $\square$

REMARK 2.14. For $b \in \mathbb{N}$, $b > 1$, set $f_b(x) = 1 + x^b + (-1)^b(x+1)^b$. Note that $f_b(x) = p_b(x, 1, -1-x)$. Let $A = \{1, a, b\}$ with $ab \equiv 0 \pmod 6$. Conjecture 2.10 for A is equivalent to $\gcd(f_a(x), f_b(x)) = 1$. We expect $f_b(x)$ to be irreducible in $\mathbb{Q}[x]$ up to the factor x and cyclotomic factors $1 + x$ or $1 + x + x^2$ which are present or not depending on b mod 6. In particular, we expect $f_b(x)$ to be irreducible $\mathbb{Q}[x]$ if $b \equiv 0 \pmod 6$. A simple computation shows that Eisenstein's criterion applies to $f_b(x+1)$ with respect to $p = 3$ for b of the form $3^u(3^v + 1)$ with $u > 0$ and $v \geq 0$. These considerations imply that, if b is of that form, then f_b is irreducible (over $\mathbb{Q}$). Hence, Conjecture 2.10 holds for $A = \{1, a, b\}$ where $a < b$ and $b = 3^u(3^v + 1)$ with $u > 0$ and $v \geq 0$.

For $n > 3$ the condition $\left(\prod_{i \in A} i\right) \equiv 0 \pmod{n!}$ does not imply that $p_A(n)$ is a regular sequence. For $n = 4$, computer experiments suggest the following conjecture.

CONJECTURE 2.15. *Let $A \subset \mathbb{N}^*$ with $|A| = 4$, say $A = \{a_1, a_2, a_3, a_4\}$, and assume* $\gcd(A) = 1$. *Then $p_A(4)$ is a regular sequence if and only if A satisfies the following conditions:*

(1) *At least two of the a_i's are even, at least one is a multiple of* 3, *and at least one is a multiple of* 4.

(2) *If E is the set of the even elements in A and $d =$* $\gcd(E)$ *then the set $\{a/d : a \in E\}$ contains an even number.*

(3) *A does not contain a subset of the form $\{d, 2d, 5d\}$.*

REMARK 2.16. (a) Condition (1) is obviously stronger than 4! divides $a_1 a_2 a_3 a_4$. For instance, the set $\{1, 3, 5, 8\}$ does not satisfy (1) and the product of its elements is divisible by 4!.

(b) The conditions (2) and (3) are independent. For example, the set $\{1, 3, 4, 12\}$ satisfies (1) but not (2) and $\{1, 2, 5, 12\}$ satisfies (1) and (2) but not (3).

(c) We can prove that conditions (1), (2) and (3) are necessary. Indeed, assume $p_A(4)$ is a regular sequence. Then (1) holds by Lemma 2.6. To get (2), consider the point $P = (x, -x, y, -y) \in \mathbb{C}^4$. Obviously P is a solution of the equation $p_k(4) = 0$ with k odd. If k is even, then $p_k(4)$ evaluated at P is $2p_k(2)$ evaluated at (x, y). Hence we see that the only common root of $p_k(2)$ with $k \in E$ is $(0, 0)$. So, by Lemma 2.4, at least one element of $\{a/d : a \in E\}$ is even. To show that (3) is necessary, note that, by degree reasons, $p_5(4)$ is in the ideal $(p_1(4), p_2(4))$. Replacing x_i by x_i^d, we see that $p_{5d}(4)$ is in the ideal $(p_d(4), p_{2d}(4))$. So (3) follows.

For complete symmetric polynomials in three variables we formulate the following conjecture.

Conjecture 2.17. *Let $A = \{a, b, c\}$ with $a<b<c$. Then $h_A(3)$ is a regular sequence if and only if the following conditions are satisfied:*

(1) $abc \equiv 0 \pmod 6$.

(2) $\gcd(a+1, b+1, c+1) = 1$.

(3) *For all $t \in \mathbb{N}$ with $t > 2$ there exist $d \in A$ such that $d + 2 \not\equiv 0, 1$* $\pmod t$.

Again, the "only if" part follows from the considerations above. For instance, if (2) does not hold then the three polynomials have a common non-zero solution of the form $(x, 1, 0)$.

A. Appendix: Non-vanishing of the coefficient a_m

We want to prove that

$$\sum_{b=0}^{\lfloor h/3 \rfloor} \frac{(-1)^{h-b}}{h-b} \binom{h-b}{2b} \left(\frac{2}{3}\right)^b \tag{A.1}$$

is non-zero except for $h = 3$.

We may assume from now on that $h > 3$. The idea is a 3-adic analysis of the summands. All of them are rational numbers. If $h \not\equiv 3, 5 \pmod 9$, then we shall show that the 3-adic valuation of the last summand (the summand for $b = \lfloor h/3 \rfloor$ is smaller than the 3-adic valuations of all other summands. In this situation, the sum cannot be zero. Similarly, if $h \equiv 3, 5 \pmod 9$, we shall show that the 3-adic valuations of the summands for $b \leq \left\lfloor \frac{h}{3} \right\rfloor - 2$ are all larger than the 3-adic valuation of the sum of the two summands for

$b = \left\lfloor \frac{h}{3} \right\rfloor$ and $b = \left\lfloor \frac{h}{3} \right\rfloor - 1$. Here, summands with $b \le \left\lfloor \frac{h}{3} \right\rfloor - 2$ do indeed exist (since we assumed that $h > 3$ which, together with $h \equiv 3, 5 \pmod 9$, implies that h must be at least $3 + 9 = 12$), and therefore the sum cannot be zero.

We write $v_3\left(\frac{r}{s}\right)$ for the 3-adic valuation of the rational number $\frac{r}{s}$ which, by definition, is 3^{a-b}, where 3^a is the largest power of 3 dividing r, and where 3^b is the largest power of 3 dividing s.

We shall use the following (well-known and easy to prove) fact: the 3-adic valuation of a binomial coefficient $\binom{m}{n}$, $v_3\left(\binom{m+n}{n}\right)$, is equal to the number of carries which occur during the addition of the numbers m and n in ternary notation. From now on, whenever we speak of "carries during addition of two numbers", we always mean the addition of these two numbers when written in ternary notation.

Case 1: $h \equiv 0 \pmod 3$. Let $h = 3k$, $k > 1$. In (A.1) replace b by $k - b$ to obtain the sum

$$\text{(A.2)} \qquad \sum_{b=0}^{k} \frac{(-1)^b}{2k+b} \binom{2k+b}{3b} \left(\frac{2}{3}\right)^{k-b}.$$

Let first $k \not\equiv 1 \pmod 3$ (i.e., $h \not\equiv 3 \pmod 9$).

For the summand in (A.2) for $b = 0$, we have

$$v_3\left(\frac{1}{2k}\left(\frac{2}{3}\right)^k\right) \le -k.$$

We claim that we have

$$\text{(A.3)} \qquad v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) > -k \quad \text{for all } b \ge 1.$$

To prove the claim we assume that $v_3(2k+b) = e$ and that $3^{s-1} \le 3b < 3^s$. Clearly $e \ge 0$ and $s \ge 2$. Using these conventions, we have

$$\text{(A.4)} \quad v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right)$$
$$= b - k - e + \#(\text{carries during addition of } 3b \text{ and } 2k - 2b).$$

Since $b \ge 1$, the inequality (A.3) holds for $e = 0$. From now on we assume that $e > 0$.

If $s > e > 0$, then from (A.4) we get

$$\begin{aligned} v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) &\geq 3^{s-2} - k - e \\ &\geq -k + 3^{e-1} - e \\ &\geq -k. \end{aligned}$$

This proves (A.3) for $e > 1$, since in this case we have actually $3^{e-1} > e$, and thus $> -k$ in the last line of the inequality chain. It also proves (A.3) for $e = 1$ and $s > 2$, since in this case we have $3^{s-2} > 3^{e-1}$, and thus we have $> -k + 3^{e-1} - e$ in the inequality chain. The only case which is left open is $e = 1$ and $s = 2$.

Let now $s \leq e$. Let us visualize the numbers $2k + b$ and $3b$ in ternary notation,

$$\begin{aligned} (2k+b)_3 &= \dots\underbrace{0\dots\dots0}_{e}, \\ (3b)_3 &= \qquad\quad \underbrace{\dots0}_{s}. \end{aligned}$$

When we add $2k - 2b$ to $3b$, then we get $2k + b$. Since $(2k + b)_3$ has 0's as s-th, $(s + 1)$-st, $\dots$, e-th digit (from the right), we must have at least $e - s + 1$ carries when adding $2k - 2b$ and $3b$. From (A.4) we then have

$$\begin{aligned} v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) &\geq 3^{s-2} - k - e + (e - s + 1) \\ &\geq -k + 3^{s-2} - s + 1 \\ &\geq -k. \end{aligned}$$

The last inequality is in fact strict if $s > 2$, proving the claim (A.3) in this case.

In summary, except for $s = 2$ and $e > 0$, the claim (A.3) is proved. However, if $s = 2$, then $b = 1$ or $b = 2$. If $b = 2$, then we have $b > 3^{s-2}$. If we use this in the first line of the inequality chains, then both of them become strict inequalities. Therefore the only case left is $b = 1$ and $e > 0$. However, if $b = 1$, then $e = v_3(2k + b) = v_3(2k + 1) = 0$ since we assumed that $k \not\equiv 1 \pmod 3$. This is absurd, and hence the claim is established completely.

Now we address the (more complicated) case that $k \equiv 1 \pmod 3$ (i.e., $h \equiv 3 \pmod 9$). In this case we combine the summands in (A.2) for $b = 0$

and $b = 1$:

$$\frac{1}{2k}\left(\frac{2}{3}\right)^k - \frac{1}{2k+1}\binom{2k+1}{3}\left(\frac{2}{3}\right)^{k-1} = -\frac{2^{k-1}}{3^k}\frac{(k-1)(2k^2+k+1)}{k}.$$

The 3-adic valuation of this expression is

$$v_3(k-1) - k.$$

Let us write $f = v_3(k-1)$, and, as before, $v_3(2k+b) = e$ and $3^{s-1} \leq 3b < 3^s$. Since $k \equiv 1 \pmod 3$, we know that $f \geq 1$. We claim that for $b \geq 2$ we have

$$v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) > -k + f. \tag{A.5}$$

Since the notation is as before, we may again use Equation (A.4) for the computation of the 3-adic valuation on the left-hand side.

For convenience, we visualize the involved numbers,

$$\begin{aligned}
(2k)_3 &= \ldots\underbrace{0\ldots\ldots\ldots02}_{f}\\
(2k+b)_3 &= \ldots\ldots\ldots\underbrace{0\ldots00}_{e}\\
(b)_3 &= \qquad\ldots\underbrace{\underbrace{2\ldots21}_{\min\{e,f\}}}_{s-1}\\
(3b)_3 &= \qquad\ldots\underbrace{\underbrace{22..210}_{\min\{e,f\}+1}}_{s}
\end{aligned}$$

For later use, we note that we must have

$$b \geq 3^{\min\{e,f\}} - 2, \tag{A.6}$$

and if $s - 1 > e$ even

$$b \geq 3^{s-2} + 3^{\min\{e,f\}} - 2. \tag{A.7}$$

Another general observation is that, if $e > 0$, then the number of carries when adding $3b$ and $2k - 2b$ must be at least

$$e + \chi(f \geq e) \cdot \max\{0, f - s + \chi(s \neq e+1)\}, \tag{A.8}$$

because there must be carries when adding up the second, third $, \ldots, (e+1)$-st digits (from the right), and because $(2k+b)_3$ has 0's as s-th,

$(s+1)$-st, ..., f-th digit. Here, $\chi(\mathcal{A}) = 1$ if $\mathcal{A}$ is true and $\chi(\mathcal{A}) = 0$ otherwise. The truth value $\chi(s \neq e+1)$ occurs because if $s = e+1$ we cannot count the carry at the $(s = e+1)$-st digit twice.

(a) $e \geq f \geq 1$. From (A.4), (A.6), and (A.8), we get

$$v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) \geq (3^f - 2) - k - e + e$$
$$\geq -k + f.$$

Moreover, if $f > 1$ then the last inequality is strict, proving the claim (A.5) in this case. The only case which remains open is $f = 1$. If $s > 2$, we could use (A.7) instead of (A.6), in which case the claim would also follow. Thus, we are left with considering the case $s = 2$ and $f = 1$. In that case, we would have $b = 1$, a contradiction.

(b) $f \geq s = e+1 \geq 2$. From (A.4), (A.6), and (A.8), we get

$$v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) \geq 3^e - 2 - k - e + (e + f - s)$$
$$\geq -k + f + 3^{s-1} - s - 2$$
$$> -k + f,$$

as long as $s > 2$. On the other hand, if $s = 2$ and, hence, $e = 1$, then we would have $b = 1$, a contradiction.

(c) $f \geq s > e+1 \geq 2$. From (A.4), (A.7), and (A.8), we get

$$v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) \geq 3^{s-2} + 3^e - 2 - k - e + (e + f - s + 1)$$
$$\geq 3^{s-2} + 3^e - 1 - k + f - s$$
$$> (s-1) + 1 - k + f - s$$
$$> -k + f,$$

since $s > 2$ and $e \geq 1$.

(d) $s > f > e \geq 1$. From (A.4), (A.7), and (A.8), we get

$$v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) \geq 3^{s-2} + 3^e - 2 - k - e + e$$
$$\geq 3^{f-1} + 3^e - 2 - k$$
$$> -k + f,$$

since $f > 1$ and $e \geq 1$.

(e) $f > e = 0$. Our previous visualization of the involved numbers then collapses to

$$(2k)_3 = \ldots\underbrace{0\ldots\ldots\ldots02}_{f}$$

$$(2k+b)_3 = \ldots\ldots\ldots\ldots\ldots$$

$$(b)_3 = \underbrace{\ldots\ldots\ldots}_{s-1}$$

$$(3b)_3 = \underbrace{\ldots\ldots\ldots0}_{s}$$

Instead of (A.6) or (A.7), we have now $b \geq 3^{s-2}$. The number of carries when adding $3b$ and $2k-2b$ must still be at least $\max\{0, f-s+1\}$. Hence, from (A.4) we get

$$v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) = 3^{s-2} - k + \max\{0, f-s+1\}. \tag{A.9}$$

If $f < s$, then we obtain from (A.9) that

$$\begin{aligned} v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) &\geq 3^{f-1} - k \\ &\geq -k + f, \end{aligned}$$

since $f \geq 1$. This inequality chain is in fact strict as long as $s > f+1$ or $f > 1$. Thus, the only case which is open is $f = 1$ and $s = 2$. In that case, we must necessarily have $b = 2$. So, instead of $b \geq 3^{s-2}$ to obtain (A.9), we could have used $b > 1 = 3^{s-2}$, again leading to a strict inequality.

If $f \geq s$, then we obtain from (A.9) that

$$\begin{aligned} v_3\left(\frac{1}{2k+b}\binom{2k+b}{3b}\left(\frac{2}{3}\right)^{k-b}\right) &\geq 3^{s-2} - k + f - s + 1 \\ &\geq -k + f, \end{aligned}$$

since $s \geq 2$. This inequality chain is in fact strict whenever $s \geq 3$. If $s = 2$ then the same argument as in the previous paragraph leads also to a strict inequality.

This completes the verification of the claim (A.5).

Case 2: $h \equiv 1 \pmod 3$. Let $h = 3k+1$, $k \geq 1$. In (A.1) replace b by $k-b$

to obtain the sum

$$\sum_{b=0}^{k} \frac{(-1)^{b+1}}{2k+b+1} \binom{2k+b+1}{3b+1} \left(\frac{2}{3}\right)^{k-b}. \tag{A.10}$$

For the summand in (A.10) for $b = 0$, we have

$$v_3\left(-\frac{1}{2k+1}(2k+1)\left(\frac{2}{3}\right)^{k}\right) = -k.$$

We claim that we have

$$v_3\left(\frac{1}{2k+b+1}\binom{2k+b+1}{3b+1}\left(\frac{2}{3}\right)^{k-b}\right) > -k$$

for all $b \geq 1$. To see this we argue as in Case 1. Everything works in complete analogy. However, what makes things less complicated here is the fact that the first digit (from the right) of $3b+1$ is a 1. Therefore there is an additional carry when adding $3b+1$ and $2k-2b$ (in comparison to the addition of $3b$ and $2k-2b$ in Case 1; namely when adding the first digits), and this implies that the complications that we had in Case 1 when $k \equiv 1 \pmod 3$ do not arise here.

Case 3: $h \equiv 2 \pmod 3$. Let $h = 3k+2$, $k \geq 1$. In (A.1) replace b by $k-b$ to obtain the sum

$$\sum_{b=0}^{k} \frac{(-1)^{b}}{2k+b+2} \binom{2k+b+2}{3b+2} \left(\frac{2}{3}\right)^{k-b}. \tag{A.11}$$

For the summand in (A.11) for $b = 0$, we have

$$v_3\left(\frac{1}{2k+2}\frac{(2k+2)(2k+1)}{2}\left(\frac{2}{3}\right)^{k}\right) = -k + v_3(2k+1).$$

Let us write $f = v_3(2k+1)$. Thus,

$$v_3\left(\frac{1}{2k+2}\frac{(2k+2)(2k+1)}{2}\left(\frac{2}{3}\right)^{k}\right) = -k + f. \tag{A.12}$$

Similarly to earlier, we assume that $e = v_3(2k+b+2)$ and that $3^{s-1} \leq 3b+3 < 3^s$. Then the analogue of (A.4) is

$$\begin{aligned} &v_3\left(\frac{1}{2k+b+2}\binom{2k+b+2}{3b+2}\left(\frac{2}{3}\right)^{k-b}\right) \\ &\qquad = b-k-e+\#(\text{carries during addition of } 3b+2 \text{ and } 2k-2b). \end{aligned} \tag{A.13}$$

For convenience, we visualize the involved numbers,

$$\begin{aligned}
(2k+1)_3 &= \dots\underbrace{0\dots\dots\dots00}_{f}\\
(2k+b+2)_3 &= \dots\dots\dots\underbrace{0\dots00}_{e}\\
(b+1)_3 &= \underbrace{\dots\underbrace{0\dots00}_{\min\{e,f\}}}_{s-1}\\
(3b+2)_3 &= \underbrace{\dots\underbrace{22..222}_{\min\{e,f\}+1}}_{s}
\end{aligned}$$

The visualization of $(3b+2)_3$ has to be taken with a grain of salt because, if $b = 3^{s-2} - 1$, then $(3b+2)_3$ has only $s-1$ digits.

For later use, we note that we must have $s-1 > \min\{e,f\}$ and

$$b \geq 3^{s-2} - 1 + \chi(e=0). \tag{A.14}$$

Moreover, if $s = 2$, then $b+1$ has just one digit and therefore necessarily $b = 1$. Another general observation is that the number of carries when adding $3b$ and $2k - 2b$ must be at least

$$e + \chi(f \geq e) \cdot (\chi(e > 0) + \max\{0, f - s + 1\}), \tag{A.15}$$

because there must be carries when adding up the first, second, …, e-th digits (from the right), because if $f \geq e > 0$ there must also occur a carry when adding up the $(e+1)$-st digits, and because $(2k+b+2)_3$ has 0's as s-th, $(s+1)$-st, …, f-th digit. If we use (A.14) and (A.15) in (A.13), then we obtain the inequality

$$\begin{aligned}
&v_3\left(\frac{1}{2k+b+2}\binom{2k+b+2}{3b+2}\left(\frac{2}{3}\right)^{k-b}\right) \qquad \text{(A.16)}\\
&\geq 3^{s-2} - 1 + \chi(e=0) - k - e + (e + \chi(f \geq e) \cdot (\chi(e > 0) + \max\{0, f - s + 1\}))\\
&\geq -k + 3^{s-2} - 1 + \chi(f \geq e) + \chi(f \geq e) \cdot \max\{0, f - s + 1\}.
\end{aligned}$$

Let first $k \not\equiv 1 \pmod 3$ (i.e., $h \not\equiv 5 \pmod 9$) or, equivalently, $f = 0$. If we do the according simplifications in (A.16), then we arrive at

$$v_3\left(\frac{1}{2k+b+2}\binom{2k+b+2}{3b+2}\left(\frac{2}{3}\right)^{k-b}\right) \geq -k + 3^{s-2} - 1 \geq -k.$$

If $s > 3$ the last inequality is in fact a strict inequality. If $s = 2$ then necessarily $b = 1$. In that case we could have used $b > 0 = 3^{s-2} - 1$ instead of (A.14), which would also lead to a strict inequality. If we compare this with (A.12), then it follows that our sum cannot vanish.

Now let $k \equiv 1 \pmod 3$ (i.e., $h \equiv 5 \pmod 9$). Equivalently, $f \geq 1$. We combine the summands in (A.11) for $b = 0$ and $b = 1$:

$$\frac{1}{2k+2}\binom{2k+2}{2}\left(\frac{2}{3}\right)^{k} - \frac{1}{2k+3}\binom{2k+3}{5}\left(\frac{2}{3}\right)^{k-1} = -\frac{2^{k-2}}{5\cdot 3^{k}}(2k+1)(2k^3+k^2-k-10).$$

The 3-adic valuation of this expression is

$$v_3(2k+1) - k = -k + f.$$

We claim that we have

$$v_3\left(\frac{1}{2k+b+2}\binom{2k+b+2}{3b+2}\left(\frac{2}{3}\right)^{k-b}\right) > -k+f$$

for all $b \geq 2$. It should be noted that $b \geq 2$ implies $s \geq 3$.

(a) $f \geq s \geq 3$. Since $s - 1 > \min\{e, f\}$, we must have $f > e$. Thus, from (A.16), we get

$$\begin{aligned} v_3\left(\frac{1}{2k+b+2}\binom{2k+b+2}{3b+2}\left(\frac{2}{3}\right)^{k-b}\right) &\geq -k + 3^{s-2} + (f - s + 1) \\ &> -k + f, \end{aligned}$$

since $s \geq 3$.

(b) $s > f \geq 0$. From (A.16), we get

$$\begin{aligned} v_3\left(\frac{1}{2k+b+2}\binom{2k+b+2}{3b+2}\left(\frac{2}{3}\right)^{k-b}\right) &\geq -k + 3^{s-2} - 1 \\ &\geq -k + \max\{1, 3^{f-1}\} - 1 \\ &\geq -k + f, \end{aligned}$$

as long as $f \geq 1$. If $f \geq 3$, the inequality chain is in fact strict. If $f = 0$ or $f = 1$ then, because of $s \geq 3$, we could have used $3^{s-2} > 1$ to obtain that the 3-adic valuation in question must be at least $-k + f = -k$. If $f = 2$ and $s > 3$, then we could have used the estimation $3^{s-2} > 3^{f-1}$ instead. The only remaining case is $f = 2$ and $s = 3$. Since we must have $s - 1 > \min\{e, f\}$, ths only options for e are $e=0$ or $e=1$. If $e=0$ then, using (A.14) and (A.15) in (A.13), we obtain

$$v_3\left(\frac{1}{2k+b+2}\binom{2k+b+2}{3b+2}\left(\frac{2}{3}\right)^{k-b}\right)=3^{s-2}-k>-k+2=-k+f.$$

Finally, if $e=1$, then from the visualization of $(3b+2)_3$ we see that there must be at least 2 carries when adding $3b+2$ and $2k-2b$ (namely when adding the first and second digits). If we use this together with (A.14) in (A.13), the we arrive at

$$v_3\left(\frac{1}{2k+b+2}\binom{2k+b+2}{3b+2}\left(\frac{2}{3}\right)^{k-b}\right)=3^{s-2}-1-k-1+2>-k+2=-k+f.$$

This completes the proof of our claim.

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