ON THE REDUCIBILITY OF CERTAIN QUADRINOMIALS

JONAS JANKAUSKAS

Abstract. In 2007 West Coast Number Theory conference Problem 007 : 14 Walsh asked to determine all irreducible polynomials of the form \( P(x) = x^i + x^j + x^k + 4 \) with integer exponents \( i > j > k > 0 \), such that for some positive integer \( l \) the polynomial \( P(x^l) \) is reducible in \( \mathbb{Z}[x] \). In this paper we prove that such polynomials are quadrinomials \( x^{4m} + x^{3m} + x^{2m} + 4 \), where \( m \) is an odd positive integer. In addition, Walsh asked for the examples of reducible quadrinomials \( x^i + x^j + x^k + n \), \( n > 4 \) with no linear or quadratic factors. We compute the examples of reducible polynomials of the form above with non-trivial factors and negative coefficient \( n \).

1. Introduction

Let \( P(x) \) be a polynomial with integer coefficients. The polynomial \( P(x) \) is called primitive, if one cannot write \( P(x) = P_1(x^l) \) for some polynomial \( P_1 \in \mathbb{Z}[x] \) and integer \( l > 1 \). The reciprocal polynomial \( x^\text{deg} PP(1/x) \) of the polynomial \( P(x) \) is denoted by \( P^*(x) \). Through the paper, reducibility shall always mean reducibility in \( \mathbb{Z}[x] \).

The following question was posed by Walsh [9] in 2007 at West Coast Number Theory conference. Let \( i > j > k \) be positive integers. Does there exist an irreducible polynomial \( P(x) = x^i + x^j + x^k + 4 \) of degree \( \text{deg} P > 17 \), such that for some integer \( l > 1 \), the polynomial \( P(x^l) \) factors in \( \mathbb{Z}[x] \)?

In addition, Walsh asked for the examples of reducible primitive quadrinomials of the form \( x^i + x^j + x^k + n \) with integer constant coefficient \( n > 4 \), which have no linear or quadratic factors. He gave one such example \( x^7 + x^5 + x^3 + 8 = (x^3 - x^2 - x + 2)(x^4 + x^3 + 3x^2 + 2x + 4) \).

The choice of the constant coefficient 4 in the polynomial \( x^7 + x^5 + x^3 + 4 \) is not accidental. A similar example is the binomial \( x^2 + 4 \) which factors after the change of variable \( x \) to \( x^2 \). The polynomials \( x^{4m} + 4b^4 \) are the exceptional case in the theorem of Capelli [12] on the reducibility of binomials. In the trinomial case, all reducible polynomials of the form \( x^i \pm x^j \pm 4 \) were completely determined by Jonassen [6]. By the theorem given in his paper [6], there are no irreducible trinomials \( P(x) = x^i \pm x^j \pm 4 \), such that for some positive integer \( l \), the polynomial \( P(x^l) \) is reducible. In contrast, there exist quadrinomials \( P(x) = x^i + x^j + x^k + 4 \) which have this property. In Section 2, we shall give a complete description of such quadrinomials.

The questions on the reducibility of trinomials and quadrinomials have received a lot of interest. The reducible trinomials and quadrinomials with all non-zero coefficients equal to 1 or -1 were investigated by Selmer [13] and Ljunggren [7]. The missing cases in

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Ljunggren’s work were settled by Mills [8]. Many important results and generalizations were established by Schinzel in the long series of papers starting with [10], [11]. In 1972 Fried and Schinzel [5] proved a deep result on the reducibility of quadrinomials. Theorems 2 and 3 in [5] state that for the fixed integers \(a, b, c, d\), any reducible quadrinomial \(P(x) = ax^i + bx^j + cx^k + d\) either factors into the product of certain polynomials of standard shape, or such polynomial has the form \(P(x) = P_1(x')\), \(l \in \mathbb{Z}\), \(l > 0\), were \(P_1 \in \mathbb{Z}[x]\) is primitive reducible quadrinomial of degree less or equal to the effectively computable constant \(C(a, b, c, d)\). Unfortunately, this constant is too large for almost any practical applications: in our case, \(C(1, 1, 1, 4) > 2^{8045222}\). In the present paper, we shall use Ljunggren’s method [7] to determine all such exceptional quadrinomials \(x^i + x^j + x^k + 4\) which appear in the question of Walsh. See [1], [4] for a good exposition on the Ljunggren’s method. More recent results on reducibility of quadrinomials can be found in [3]. For efficient factoring algorithms, we refer to [2].

2. Main results

The following theorem gives an answer to the first question of Walsh. We note that in this paper we do not use the same terminology as in [9].

**Theorem 1.** The only primitive irreducible polynomial \(P \in \mathbb{Z}[x]\) of the form \(P(x) = x^i + x^j + x^k + 4, i > j > k > 0\), such that the polynomial \(P(x^l)\) for some positive integer \(l\) factors in \(\mathbb{Z}[x]\), is the polynomial \(P(x) = x^i + x^j + x^k + 4\). More precisely, for \(l = 2\),

\[
P(x^2) = x^8 + x^6 + x^4 + 4 = (x^4 - x^3 + x^2 - 2x + 2)(x^4 + x^3 - x^2 + 2x + 2).
\]

Indeed, if the polynomial \(P(x) = x^i + x^j + x^k + 4\) has the property asked in the Problem 007 : 14, then \(P(x) = P_1(x^m)\) for some primitive polynomial \(P_1(x)\) and some positive integer \(m\). By Theorem 1, \(P_1(x) = x^4 + x^3 + x^2 + 4\). In Lemma 2 bellow, we prove that \(P(x^l)\) is reducible only for even values \(l = 2g\); in this case the polynomial \(P(x^l)\) splits into two irreducible factors \(x^{4g} - x^{3g} + x^{2g} - 2x^g + 2\) and \(x^{4g} + x^{3g} + x^{2g} + 2x^g + 2\).

**Lemma 2.** Let \(P(x) = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0\) be a monic integer polynomial, such that \(|a_0| = p^2 > |a_1| + |a_2| + \cdots + |a_{d-1}| + 1\), where \(p\) is a prime. Let \(l > 1\) be a positive integer, such that \(P(x^l)\) is reducible in \(\mathbb{Z}[x]\) but \(P(x^m)\) is irreducible for any positive integer \(m < l\) which divides \(l\). Then \(l\) is even and \(P(x^l) = \pm Q(x)Q(-x)\), \(Q \in \mathbb{Z}[x]\). Moreover, for any integer \(r \geq 1\), both factors \(Q(\pm x^r) \in \mathbb{Z}[x]\) are irreducible.

In Lemma 3 we shall determine all the possible forms the product polynomial \(PP^*\) can take. This will be used in the proof of Theorem 1.

**Lemma 3.** Let \(P\) be a quadrinomial \(P(x) = x^i + x^j + x^k + 4\) with the integer exponents \(i > j > k > 0\). Then the polynomial \(PP^*\) takes one of the following forms:

1) \(4x^{2i} + x^{2i-k} + x^{2i-j} + x^{i+j-k} + 4x^i + 4x^{i+k} + 19x^i + 4x^{i-k} + 4x^{i-j} + x^{i-j+k} + x^j + x^k + 4\),

\[
\text{if} \quad i \neq 2j, \quad i \neq 2k; \quad j \neq 2k; \quad i + k \neq 2j; \quad i \neq j + k;
\]

2) \(4x^{2i} + x^{2i-k} + 5x^{2i-j} + x^{i+j-k} + 4x^{i+k} + 19x^i + 4x^{i-k} + x^{i-j+k} + 5x^j + x^k + 4\),
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if \( i = 2j, \ i \neq 2k, \ j \neq 2k, \ i + k \neq 2j, \ i \neq j + k; \)
3) \( 4x^{2i} + 5x^{2i-k} + x^{2i-j} + x^{i+j-k} + 4x^{i+j} + 19x^i + 4x^{i-j} + x^{i-j+k} + x^j + 5x^k + 4, \)
if \( i \neq 2j, \ i = 2k, \ j \neq 2k, \ i + k \neq 2j, \ i \neq j + k; \)
4) \( 4x^{2i} + x^{2i-k} + x^{2i-j} + 5x^{i+j-k} + 4x^{i+j} + 19x^i + 4x^{i-j} + 5x^{i-j+k} + x^j + x^k + 4, \)
if \( i \neq 2j, \ i \neq 2k, \ j \neq 2k, \ i + k \neq 2j, \ i \neq j + k; \)
5) \( 4x^{2i} + x^{2i-k} + 2x^{2i-j} + 4x^{i+j} + 4x^{i+k} + 19x^i + 4x^{i-k} + 4x^{i-j} + 2x^j + x^k + 4, \)
if \( i \neq 2j, \ i \neq 2k, \ j \neq 2k, \ i + k \neq 2j, \ i \neq j + k; \)
6) \( 4x^{2i} + 5x^{2i-k} + 5x^{2i-j} + x^{i+j-k} + 19x^i + x^{i-j+k} + 5x^j + 5x^k + 4, \)
if \( i \neq 2j, \ i \neq 2k, \ j \neq 2k, \ i + k \neq 2j, \ i = j + k; \)
7) \( 4x^{2i} + x^{2i-k} + 5x^{2i-j} + 5x^{i+j-k} + 19x^i + 5x^{i-j+k} + 5x^j + x^k + 4, \)
if \( i = 2j, \ i \neq 2k, \ j = 2k, \ i + k \neq 2j, \ i \neq j + k; \)
8) \( 4x^{2i} + 5x^{2i-k} + 2x^{2i-j} + 4x^{i+j} + 19x^i + 4x^{i-j} + 2x^j + 5x^k + 4, \)
if \( i \neq 2j, \ i = 2k, \ j \neq 2k, \ i + k = 2j, \ i \neq j + k; \)
9) \( 4x^{2i} + 5x^{2i-k} + 6x^{2i-j} + 19x^i + 6x^j + 5x^k + 4, \)
if \( i \neq 2j, \ i \neq 2k, \ j = 2k, \ i + k = 2j, \ i = j + k; \)

3. Computations

In order to answer the second part of the problem 007 : 14, we have used the computer to search for the examples of reducible polynomials of the form \( P(x) = x^i + x^j + x^k + n. \) Since the polynomial \( P(x) \) has no roots of modulus less or equal to 1 if \( n \geq 4, \) the polynomial \( P(x) \) is irreducible provided the coefficient \( n \) is equal to the prime integer \( p \geq 5. \) With MAPLE computer algebra package we factored all primitive quadrinomials \( P(x) \) with composite constant coefficient \( n \) and exponents \( i, j, k \) in the range \( 5 \leq n \leq 120, \ i - j \leq 20, \ j - k \leq 20, \ k \leq 20. \) In addition, we factored all primitive quadrinomials \( P(x) \) of this form satisfying inequalities \( 120 < n \leq 1000, \ i - j \leq 15, \ j - k \leq 15, \ k \leq 15. \) We also searched for the irreducible polynomials \( P(x) \), such that \( P(x^l) \) is reducible for some integer \( l \) in the range \( 5 < n \leq 120, (i - j)l \leq 12, (j - k)l \leq 12, kl \leq 12. \) In all the cases reducible polynomials \( P(x) \) had a factor of the form \( Q(x^l) \), where \( Q(x) \) was a linear polynomial or a quadratic polynomial. The example \( x^7 + x^5 + x^3 + 8 \) of Walsh was the only notable exception. However, it does not seem easy to prove this.

All found examples of reducible quadrinomials \( P(x) \) had two or three irreducible factors. During the preparation of this paper, A. Schinzel sent a short remark that any irreducible polynomial dividing the quadrinomial \( P(x) \) has constant coefficient greater than 1, hence the number of irreducible factors cannot exceed \( \Omega(n) \), the total number of prime factors of \( n. \) The sharpness of this estimate may be shown by the example
\[
x^{12} + x^8 + x^4 + 52 = (x^2 - 2x + 2)(x^2 + 2x + 2)(x^8 - 3x^4 + 13).
\]
Since $\Omega(n) \leq \log n / \log 2$, the number $\log n / \log 2$ is the best known bound for the total number of prime factors of the quadrinomials $P(x)$ in question.

Finally, we note that there exist the examples of reducible quadrinomials $P(x)$ with no linear or quadratic factors and negative coefficient $n < -5$, namely, the polynomials
\[
x^6 + x^4 + x^2 - 16 = (x^3 - 3x^2 + 5x - 4)(x^3 + 3x^2 + 5x + 4),
\]
\[
x^{12} + x^8 + x^4 - 16 = (x^3 - x^2 - x + 2)(x^3 + x^2 - x - 2)(x^6 + 3x^4 + 5x^2 + 4),
\]
\[
x^7 + x^3 + x^2 - 98 = (x^3 - x^2 + 2x - 7)(x^4 + x^3 - x^2 + 4x + 14),
\]
and
\[
x^{17} + x^{14} + x^8 - 16 = (x^5 + x^3 - x^2 - 2)(x^{12} - x^{10} + 2x^9 + x^8 - x^7 + x^6 + 2x^4 + 4x^3 - 4x^2 + 8).
\]

4. Proofs

Proof of Lemma 2. Let $P(x^l) = Q(x)R(x)$ for some integer $l > 0$ and polynomials $Q, R \in \mathbb{Z}[x]$. The inequality $|a_0| > |a_1| + |a_2| + \cdots + |a_d| + 1$ implies that $P, Q$ and $R$ have no roots of modulus $|z| \leq 1$. Thus the constant terms of $Q$ and $R$ are equal to $\pm p$ and they are irreducible in $\mathbb{Z}[x]$. Otherwise one of the polynomials $Q$ or $R$ would be divisible by the monic non-constant polynomial $S \in \mathbb{Z}[x]$ with the constant term $S(0) = \pm 1$. This is impossible, since such a polynomial $S$ has at least one root of modulus less or equal to 1. The same argument also implies the irreducibility of polynomials $Q(x^r)$ and $R(x^r)$ which divide $P(x^r)$.

Now, assume that the exponent $l$ has the property that for any positive integer $m < l$ which divides $l$, the polynomial $P(x^m)$ is irreducible. If $m = 1$, this means that $P(x)$ is irreducible. Let $\alpha$ be the root of the irreducible factor $Q(x)$. Since $P(x^l) = Q(x)R(x)$, the power of this root $\beta = \alpha^l$ is the root of the irreducible polynomial $P$. Let $K = \mathbb{Q}(\beta), L = \mathbb{Q}(\alpha), K \subset L$. Let $g$ be the degree $[L : K]$. The absolute norm of an algebraic integer $\beta$ over $\mathbb{Q}$ $N_{L/\mathbb{Q}}(\beta) = N_{L/\mathbb{Q}}(\alpha^l) = N_{L/\mathbb{Q}}(\alpha)^l = \pm p^l$. In the other hand, by the relative norm property, $N_{L/\mathbb{Q}}(\beta) = N_{K/\mathbb{Q}}(\beta)[L:K] = \pm p^g$. Thus $l = 2g$.

Since $l$ is even, the number $-\alpha$ is the root of $P(x^l)$. The irreducible polynomial $Q(-x)$ divides $P(x^l)$. Then $R(x) = \pm Q(-x)$. Indeed, otherwise $Q(-x) = -Q(x)$ or $Q(-x) = Q(x)$. The first case is impossible: the identity $Q(-x) = -Q(x)$ with $x = 0$ implies $Q(0) = P(0) = 0$, contradicting the inequality $|a_0| > 1$. The second identity $Q(-x) = Q(x)$ implies $Q(x) = T(x^2)$ for the polynomial $T \in \mathbb{Z}[x]$, thus $R(x) = P(x^l)/Q(x) = P(x^{2g})/T(x^2) = S(x^2), S \in \mathbb{Z}[x]$. This leads to the expression $P(x^{2g}) = T(x^2)S(x^2)$, hence $P(x^g) = T(x)S(x)$. This implies that $P(x^g)$ is reducible for the integer $g$ which is a proper divisor of $l$, contradicting the condition of Lemma 2. \hfill QED

Proof of Lemma 3. Assume that integers $i, j, k$ satisfy the inequality $i > j > k > 0$. The reciprocal of the polynomial $P(x) = x^i + x^j + x^k + 4$ is $P^*(x) = 4x^i + x^{i-k} + x^{i-j} + 1$. The product $F = PP^*$ takes the form
\[
F(x) = 4x^{2i} + x^{2i-k} + x^{2i-j} + 4x^{i+j} + x^{i+j-k} + 4x^{i+k} + 4x^{i-k} + x^{i-j+k} + 4x^{i-j} + x^{i+j} + x^k + 4.
\]
Let
\[ v_1 = 2i, \quad v_2 = 2i - k, \quad v_3 = 2i - j, \quad v_4 = i + j, \quad v_5 = i + j - k, \quad v_6 = i + k, \quad v_7 = i, \]
\[ v_8 = i - k, \quad v_9 = i - j + k, \quad v_{10} = i - j, \quad v_{11} = j, \quad v_{12} = k, \quad v_{13} = 0. \]
The multi-set \( V = \{ v_r, r = 0 \ldots 13 \} \) contains all possible exponents which appear in the polynomial \( F \). If none of them are equal, \( F \) takes the form in Case 1. We shall classify all other cases where some exponents \( v_r \) and \( v_s, r \neq s \) are equal, and the terms of \( F \) with equal exponents add together. Set
\[
e_1 = \{ i = 2j \}, \quad e_2 = \{ i = 2k \}, \quad e_3 = \{ j = 2k \}, \quad e_4 = \{ i + k = 2j \}, \quad e_5 = \{ i + j + k \}.
\]
The elements of the set \( E = \{ e_r, r = 1 \ldots 5 \} \) denote the linear relations among the integers \( i, j, k \). Note that \( v_1 \) and \( v_{13} \) are the largest and smallest integers in \( V \). Since \( i > j > k > 0 \), all the exponents \( v_1, v_2, v_3, v_4, v_5, v_6 \) are strictly greater than the exponent of the middle term \( v_7 = i \), exponents \( v_8, v_9, v_{10}, v_{11}, v_{12}, v_{13} \) are strictly less than \( v_7 = i \). \( F \) is self-reciprocal, since \( F = PP^* = F^* \). Hence \( v_s = 2i - v_{13-s+1}, s = 8 \ldots 13 \). Thus it suffices to check all possible cases when some of the integers \( v_2, v_3, v_4, v_5, v_6 \) are equal. Observe that
\[ v_2 > v_3, \quad v_2 > v_5, \quad v_4 > v_5, \quad v_4 > v_6. \]
Hence, all possible pairs of equal exponents \( v_s, s = 2 \ldots 6 \) are: \( v_2 = v_4 \) (this is equivalent to the linear relation \( e_5 \)), \( v_2 = v_6 \) (equivalent to \( e_2 \)), \( v_3 = v_4 (e_1) \), \( v_3 = v_5 (e_4) \), \( v_3 = v_6 (e_5) \), \( v_5 = v_6 (e_3) \). The remaining pairs of equal exponents \( v_s, s = 8 \ldots 13 \) are determined uniquely by the symmetry \( v_s = 2i - v_{13-s+1} \).

The forms of the polynomial \( F \) where the integer exponents \( i, j, k \) satisfy precisely one linear relation in the set \( E \) are listed in Cases (2)-(6). In order to check Cases (2)-(6), use the expression in Case (1) and add terms with equal powers \( x^{v_r} \) and \( x^{v_s} \) together if \( v_r = v_s \). The next step is to determine all possible forms of \( F \) where the integers \( i, j, k \) satisfy two linear relations \( \{ e_s, e_t \} \subset E \). Observe that no one pair of the linear relations \( \{ e_1, e_2 \}, \{ e_1, e_4 \}, \{ e_2, e_3 \}, \{ e_2, e_5 \} \) is possible if \( i > j > k > 0 \). The possible pairs are \( \{ e_1, e_3 \}, \{ e_2, e_4 \}, \{ e_3, e_4 \}, \{ e_3, e_5 \}, \{ e_4, e_5 \} \). Consider the pair \( \{ e_1, e_3 \} \) as a system of two linear equations in three integer variables \( i, j, k \). All positive integer solutions of this system are vectors \( (i, j, k) = (4u, 2u, u) \), \( u \in \mathbb{Z}, u > 0 \). In this case, the form of the polynomial \( F \) with equal exponents \( v_3 = v_4, v_5 = v_6, v_8 = v_9, v_{10} = v_{11} \) is described in Case (7) of Lemma 3. Similarly, the integer solutions to the equations \( \{ e_2, e_4 \} \) are \( (i, j, k) = (4u, 3u, 2u), u \in \mathbb{Z}, u > 0 \) and \( F \) takes the form given in Case 8. Observe that all the pairs of equations from the system \( \{ e_3, e_4, e_5 \} \) are equivalent and have the solution \( (i, j, k) = (3u, 2u, u), u \in \mathbb{Z}, u > 0 \). Hence, any two of the three relations \( \{ e_3, e_4, e_5 \} \) imply the third one. This situation is depicted in Case 9. It remains to show that there are no other cases when three or more linear relations \( e_s \in E \) hold. Indeed, in such case three different pairs of linear relations, other than all 3 possible pairs from the set \( \{ e_3, e_4, e_5 \} \) must be satisfied. There would be at least one of pairs \( \{ e_1, e_3 \}, \{ e_2, e_4 \} \) and one pair from the set \( \{ e_3, e_4, e_5 \} \). This is impossible, since all the intersections of the sets of integer triples \( (i, j, k) \) which satisfy such linear relations
\[
\{(4u, 2u, u), u \in \mathbb{Z}, u > 0 \}, \quad \{(4u, 3u, 2u), u \in \mathbb{Z}, u > 0 \}, \quad \{(3u, 2u, u), u \in \mathbb{Z}, u > 0 \}
\]
are empty.

Sketch of the proof of Theorem 1. Before proceed to prove Theorem 1, we give the sketch of the proof. First, we show that any primitive quadrinomial $P(x) = x^i + x^j + x^k + 4$ in question whose exponents $(i, j, k)$ satisfy a certain linear relation is precisely the quadrinomial $x^4 + x^3 + x^2 + 4$. Secondly, we consider the polynomial $G(x) = Q(-x)Q^*(x)$, where $Q$ is the polynomial from the factorization $P(x^l) = \pm Q(x)Q(-x)$. This factorization is a consequence of Lemma 2. We determine the form of the polynomial $G$ using reduction modulo 2 and the identity $|P| = |G|$ for the Euclidean norms of $P$ and $G$. Recall that the Euclidean norm $|f|$ of the polynomial $f(x) = \sum_{s=1}^{\deg f} a_j x^j \in \mathbb{Z}[x]$ is defined as $|f| = (\sum_{s=1}^{\deg f} a_j^2)^{1/2}$. Following [7], we refer to the equality $|P| = |G|$ as the identity of Ljunggren. Thirdly, we use the expression $GG^*(x) = PP^*(x^4)$ and compare $PP^*(x^4)$ from Lemma 3 to $GG^*(x)$. We establish that the case $x^4 + x^3 + x^2 + 4$ is the only one possible.

Proof of Theorem 1. First suppose that the exponents $i, j, k$ of $P(x) = x^i + x^j + x^k + 4$ satisfy linear relations $i = 2k$ and $i + k = 2j$. Then $(i, j, k) = (4u, 3u, 2u)$ for some positive integer $u$ so $P(x) = x^{4u} + x^{3u} + x^{2u} + 4$, which is primitive for $u = 1$. A simple computer shows that the polynomial $P_1(x) = x^4 + x^3 + x^2 + 4$ is irreducible, and $P_1(x^2) = (x^4 - x^3 + x^2 - 2x + 2)(x^4 + x^3 + x^2 + 2x + 2)$. For even integers $l = 2g > 0$ the polynomial $P_1(x^l)$ splits in $\mathbb{Z}[x]$ into $P_1(x^l) = (x^{4g} - x^{3g} + x^{2g} - 2x^g + 2)(x^{4g} + x^{3g} + x^{2g} + 2x^g + 2)$. By Lemma 2, both factors are irreducible. By Lemma 2, $P_1(x^l)$ is irreducible for odd exponents $l$. Below we shall show that this case is the only possible. Note that the linear relations $i = 2k, i + k = 2j$ appear in the Case (8) of Lemma 3. Hence we have to prove that every quadrinomial $P(x)$ in the question of Walsh satisfies $P(x^l)P^*(x^l) = F(x^l)$, where $F$ is a polynomial in Case (8) of Lemma (3).

Let $P(x) = x^i + x^j + x^k + 4$ be an irreducible polynomial and $l > 0$ be an integer such that $P(x^l)$ splits in $\mathbb{Z}[x]$, while $P(x^m)$ is irreducible for any integer $m$, $1 \leq m < l$ dividing the exponent $l$. By Lemma 2, $l = 2g, g \in \mathbb{Z}$, and $P(x^l) = \pm Q(x)Q(-x)$. Without loss of generality, we may assume that $Q(x)$ is monic. Then $P(x^l) = (-1)^gQ(x)Q(-x)$. The polynomials $Q(x)$ and $Q(-x)$ have equal constant terms $\pm 2$, hence $P(x) = Q(x)Q(-x)$. This implies that the degree $ig$ is even. Also, $Q(0) = 2$. Otherwise $Q(x)$ has a positive real root which is impossible, since $P(x) > 0$ if $x > 0$. Consider the reduction of $P(x^g)$ modulo 2:

$$P(x^g)^2 \equiv P(x^{2g}) = Q(x)Q(-x) \equiv Q(x)^2 \pmod{2}.$$ 

Hence $Q(x) \equiv P(x^g) \equiv x^{ig} + x^{jg} + x^{kg} \pmod{2}$. Let $G$ be the product $G(x) = Q(-x)Q^*(x)$ of degree $2ig$. Note that the polynomial $G$ satisfies the identity $x^{2ig}G(1/x) = (-1)^gG(-x)$. Since $ig$ is even, $G^*(x) = G(-x)$. Hence the integer coefficients of $G(x) = \sum_{s=0}^{2ig} b_s x^s$ which are symmetric with respect of middle term are equal in modulus, more precisely,

$$b_s = (-1)^s b_{2ig-s}, 0 \leq s \leq 2ig. \tag{1}$$

Reduce $G(x)$ modulo 2:

$$G(x) = Q^*(x)Q(-x) \equiv Q^*(x)Q(x) \equiv (x^{(i-k)g} + x^{(i-j)g} + 1)(x^{ig} + x^{jg} + x^{kg}) \equiv x^{(2i-k)g} + x^{(2i-j)g} + x^{(i+j-k)g} + x^{ig} + x^{(i-j+k)g} + x^{jg} + x^{kg} \pmod{2}. \tag{2}$$
Note that in (2) the commuting of the operation $\ast$ and reduction \pmod{2} is essentially used, which make sense since $f^\ast(x) \equiv (f(x) \pmod{2})^\ast$ if and only if the leading coefficient of $f \in \mathbb{Z}[x]$ is odd.

Since $Q$ is monic, $Q(0) = 2$, the leading and constant coefficients of $G$ are equal to 2. Since $i > j > k > 0$, the exponents in $G$ modulo 2 satisfy the inequalities
\[
(2i - k)g > (2i - j)g > (i + j - k)g > ig > (i - j + k)g > jg > kg,\]
provided $i + k > 2j$ or
\[
(2i - k)g > (i + j - k)g > (2i - j)g > ig > jg > (i - j + k)g > kg,
\]
provided $i + k < 2j$. Hence the polynomial $G(x)$ in (2) has 7 odd coefficients if $i + k \neq 2j$. If $i + k = 2j$, $G(x)$ modulo 2 takes the form
\[
G(x) \equiv x^{(2i-k)g} + x^{ig} + x^{kg} \pmod{2}, \tag{3}
\]
with 3 odd coefficients. Observe that $P(x^2)P(x^t) = G(x)G^\ast(x)$. The equality holds since $(Q^\ast)^\ast = Q$ which is true since $Q(0) \neq 0$. By the identity of Ljunggren, $|G|^2 = |P|^2 = 1^2 + 1^2 + 1^2 + 4^2 = 19$. The leading and constant coefficients of $G$ are equal to 2, thus the sum of squares of coefficients $b_s, 1 \leq s \leq 2ig - 1$ is equal to 11. In addition, there must be precisely 3 or 7 odd coefficients by (2) and (3). All such possible sums of squares are
\[
11 = 3^2 + 1^2 + 1^2 = 2^2 + 2^2 + 1^2 + 1^2 + 1^2 = 2^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 \tag{4}
\]
The absolute values of the coefficients of $G$ are symmetric with respect to the middle term $b_g \equiv 1 \pmod{2}$. Thus an integer which appears in the sum of squares above the odd number of times must be the absolute value of the middle coefficient $b_g$. Hence the summands in the third sum in (4) cannot be the squares of coefficients of the polynomial $G$. This implies that $G$ has 3 odd coefficients and the exponents $i, j, k$ satisfy the relation $i + k = 2j$. Using the identities (1), (3), and (4) we deduce that $G$ takes one of the forms:
\[
G(x) = 2x^{2ig} + \varepsilon x^{(2i-k)g} + 3\delta x^{ig} + (-1)^kg \varepsilon x^{kg} + 2, \tag{5}
\]
\[
G(x) = 2x^{2ig} + \varepsilon_1 x^{(2i-k)g} + 2\varepsilon_2 x^{t+ig} + \delta x^{ig} + (-1)^t 2\varepsilon_2 x^{ig-t} + (-1)^kg \varepsilon_1 x^{kg} + 2, \tag{6}
\]
the coefficients $\varepsilon, \varepsilon_1, \varepsilon_2, \delta$ are all equal to $-1$ or 1 and $t$ is an integer $0 < t < ig$. Also, note that the terms $x^{t+ig}, x^{ig-t}$ do not coincide with any other term of the polynomial $G$ in (6) by (4). We shall determine the coefficients $\varepsilon, \varepsilon_1, \varepsilon_2, \delta$. Observe that $G(1) = Q(1)Q(-1) = P(1) = 7$. In (5), this is possible if and only if $\delta = 1$ and $\varepsilon + (-1)^kg \varepsilon_1 = 0$, hence the exponent $kg$ is odd in (5). Moreover, we may assume that $\varepsilon = 1$. Otherwise, replace $x$ by $-x$. Thus $G$ in (5) takes the form
\[
G(x) = 2x^{2ig} + x^{(2i-k)g} + 3x^{ig} - x^{kg} + 2, \tag{ii}
\]
Consider $G$ in (6). There are three cases where $G(x)$ takes the value $G(1) = 7$:

a) $2 \mid kg, 2 \nmid t, \varepsilon_1 = 1, \delta = 1$. Assume that $\varepsilon_2 = 1$, otherwise change $x$ to $-x$;

b) $2 \mid t, 2 \nmid kg, \varepsilon_2 = 1, \delta = -1$. Assume that $\varepsilon_1 = 1$, otherwise change $x$ to $-x$;

c) $2 \mid kg, 2 \nmid t, \varepsilon_1 = -1, \varepsilon_2 = 1, \delta = 1$.

The polynomial $G$ in Cases (a), (b), (c) takes the forms (ii), (iii), (iv) below, respectively.
Thus \( g_i \) coincide with the term 4 negative terms. Hence (4) second leading term of \( x \) implies Case (8) of Lemma 3.

Next, assume that \( G(x)G^*(x) = P(x^2g)P^*(x^2g) = F(x^2g) \), where \( F(x) \) is one of the polynomials in Lemma 3. Since \( i + k = 2j \), it suffices to check Cases (5), (8), (9) in Lemma 3. First, assume that \( G \) takes the form (i). Then

\[
G(x)G^*(x) = 4x^{4g} + 12x^{3ig} - x^{(4i-2k)g} + 19x^{2ig} - x^{2kg} + 12x^{ig} + 4
\]

has 7 non-zero coefficients, hence it must coincide with \( F(x^{2g}) \) in Case (9) of Lemma 3. This is impossible, since the coefficients of \( F \) are different from the coefficients of \( GG^* \).

Next, assume that \( G \) takes the form (iii). Compute the product \( GG^* \) modulo 4:

\[
G(x)G^*(x) \equiv -x^{(4i-2k)g} - x^{2ig} - x^{2kg} \pmod{4}.
\]

None of the polynomials \( F \) in Lemma 3 satisfy \( F(x^{2g}) \equiv G(x)G^*(x) \pmod{4} \). Thus the form (iii) is impossible.

Assume that \( G \) takes the form (iv). The integer \( 2ig \) is largest exponent in \( G \). Let \( v \) be the second largest exponent in \( G \). Clearly, \( v = (2i - k)g \) or \( v = t + ig \). Observe that \( 2ig + v > s + r \) if at least one inequality \( r \leq 2ig, s \leq v \) is strict. Hence the second largest exponent in \( GG^* \) is \( 2ig + v \). Thus the first two terms of \( GG^* \) are \( x^{4ig} - 4x^{(4i-k)g} \) if \( (2i - k)g > t + ig \) or \( x^{4ig} + 8x^{3ig+t} \) if \( (2i - k)g < t + ig \). Such terms do not occur in any polynomial in Lemma 3. Hence we reject the form (iv).

This implies that \( G \) takes the form (ii). The product \( GG^* \)

\[
G(x)G^*(x) = 4x^{4ig} + 4x^{(4i-k)g} - 4x^{2t+2ig} + x^{(4i-2k)g} + 4x^{3ig} + 2x^{(3i-k)g} + 4x^{(2i+k)g} + 19x^{2ig} + 4x^{(2i-k)g} + 2x^{(i+k)g} + 4x^{ig} + x^{2kg} - 4x^{2ig-2t} + 4x^{kg} + 4.
\]

Thus \( GG^* \) coincides with the polynomial \( F(x^{2g}) \) in Case (5), (8) or (9) of Lemma 3, since \( i + k = 2j \) in (ii). Since \( i > k > 0 \), the integer \( 4i - k \) is strictly greater than \( 3i, 4i - 2k, 3i - k, 2i + k \). If \( (4i - k)g > 2ig + 2t \), then the second leading term of \( GG^* \) is \( 4x^{(4i-k)g} \). This leads directly to the Case (8) of the Lemma 3. Indeed, only polynomials \( F(x) \) in Case (5) or Case (8) have terms with coefficients equal to 4 which are not leading nor constant terms. The term with the second highest exponent \( 4x^{(4i-k)g} \) in \( GG^* \) must coincide with the term \( 4x^{2(i+j)g} \) or \( 4x^{2(i+k)g} \) in \( F(x^{2g}) \) in Case (5). Since \( j > k \), the exponent \( 2(i + j)g \) is greater than \( 2(i + k)g \). Thus \( (4i - k)g = 2(i + j)g \), so \( 4i - k = 2i + 2j \). Together with the identity \( i + k = 2j \) in Case (5) the linear relation \( 4i - k = 2i + 2j \) implies \( i = 2k \), which implies Case (8) of Lemma 3.

Hence we may assume that \( (4i - k)g \leq 2ig + 2t \). If the inequality is strict, then the second leading term of \( GG^* \) is \(-4x^{2g+2t}\). However, the polynomials in Lemma 3 have no negative terms. Hence \( (4i - k)g = 2ig + 2t \). Thus

\[
GG^* = 4x^{4ig} + x^{(4i-2k)g} + 4x^{3ig} + 2x^{(3i-k)g} + 4x^{(2i+k)g} + 19x^{2ig} + 4x^{(2i-k)g} + 2x^{(i+k)g} + 4x^{ig} + x^{2kg} + 4.
\]
Let $F(x)$ be the polynomial in Case (5) of Lemma 3. Replace $x$ by $x^{2g}$ and use the identity $2j = i + k$. The resulting polynomial

$$F(x^{2g}) = 4x^{4ig} + x^{(4i-2k)g} + 2x^{(4i-2j)g} + 4x^{(2i+2j)g} + 4x^{(2i+2k)g} + 19x^{2ig} + 4x^{(2i-2k)g} + 4x^{(2i-2j)g} + 2x^{2jg} + x^{2kg} + 4$$

$$= 4x^{4ig} + x^{(4i-2k)g} + 2x^{(3i-k)g} + 4x^{(3i+k)g} + 4x^{(2i+2k)g} + 19x^{2ig} + 4x^{(2i-2k)g} + 4x^{(i-k)g} + 2x^{(i+k)g} + x^{2kg} + 4.$$

The difference $F(x^{2g}) - GG^* = 4x^{(3i+k)g} + 4x^{(2i+2k)g} + 4x^{(2i-2k)g} + 4x^{(i-k)g} - 4x^{3ig} - 4x^{(2i+k)g} - 4x^{(2i-k)g} - 4x^{ig} \neq 0$, since the exponent $(3i + k)g$ is the larger than other exponents in $F(x^{2g}) - GG^*$. Thus $GG^*$ does not coincide with a polynomial given in Case (5) of Lemma 3.

Let $F(x)$ be the polynomial in Case (9) of Lemma 3. The equations $j = 2k, 2j = i + k, i = j + k$ imply $(i, j, k) = (3u, 2u, u), u \in \mathbb{Z}, u > 0$. Hence

$$GG^* = 4x^{12ug} + x^{10ug} + 4x^{9ug} + 2x^{8ug} + 4x^{7g} + 19x^{6ug} + 4x^{5ug} + 2x^{4ug} + 4x^{3ug} + x^{2ug} + 4.$$

Also, $F(x^{2g}) = 4x^{12ug} + 5x^{10ug} + 6x^{9ug} + 19x^{6ug} + 6x^{4ug} + 5x^{2ug} + 4$ and $F(x^{2g}) \neq GG^*$, so Case (9) is impossible. Hence we conclude that Case (8) is the only one possible. This completes the proof. \qed

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References

DEPARTMENT OF MATHEMATICS AND INFORMATICS, VILNIUS UNIVERSITY, NAUGARUKO 24, VILNIUS LT-03225, LITHUANIA

E-mail address: jonas.jankauskas@gmail.com