Squarefree values of polynomials all of whose coefficients are 0 and 1

by

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1. Introduction. Let \( n \) be a non-negative integer and consider the set of polynomials

\[ S_n = \left\{ f(x) = \sum_{j=0}^{n} \varepsilon_j x^j : \varepsilon_j \in \{0, 1\} \text{ for each } j \text{ and } \varepsilon_0 = 1 \right\}. \]

The condition \( \varepsilon_0 = 1 \) ensures that the elements of \( S_n \) are not divisible by \( x \). Let

\[ S = \bigcup_{n=0}^{\infty} S_n. \]

There are interesting open problems concerning the polynomials in \( S \). Using the main result in [1] (with base 2) or using the well-known explicit formula for the number of irreducible polynomials of degree \( \leq n \) modulo 2, one can easily show that there are at least on the order of \( 2^n/n \) irreducible polynomials in \( S_n \). Odlyzko (private communication) has asked whether almost all polynomials in \( S \) are irreducible. In other words, does

\[ \lim_{n \to \infty} \frac{|\{f(x) \in S_n : f(x) \text{ is irreducible}\}|}{2^n} = 1? \]

It is not even known how to establish that the limit (or the limit supremum) is positive. Another open problem, posed by Odlyzko and Poonen [2], is to determine whether it is true that if \( \alpha \) is a root with multiplicity > 1 of some polynomial \( f(x) \) in \( S \), then \( \alpha \) is a root of unity.

The purpose of this paper is to establish two results concerning the polynomials in \( S \). First, we shall show

**Theorem 1.** Let \( b = 3, 4, \) or \( 5 \). Then there are infinitely many polynomials \( f(x) \in S \) for which \( f(b) \) is squarefree. Moreover, for such \( b \), the
The density of polynomials \( f(x) \in S \) for which \( f(b) \) is squarefree is

\[
\lim_{n \to \infty} \frac{|\{f(x) \in S_n: f(b) \text{ is squarefree}\}|}{2^n} = \frac{6}{\pi^2} \prod_{p | \mathcal{b}} \left(1 - \frac{1}{p^2}\right)^{-1}.
\]

There are other trivial values of \( b \) for which one can obtain similar results (when \( |b| \leq 2 \)), but we do not know how to establish the analogous results for \( b \geq 6 \). As an immediate consequence of Theorem 1, we deduce the

**Corollary.** Let \( b = 3, 4, \) or \( 5 \). There are infinitely many squarefree numbers in base \( b \) consisting only of the digits 0 and 1.

The arguments can be modified slightly to allow for the possibility that \( \varepsilon_0 = 0 \) in the definition of \( S_n \). Thus, for \( b = 3, 4, \) or \( 5 \), we can obtain the density of squarefree numbers in base \( b \) among the positive integers consisting only of the digits 0 and 1 in base \( b \). For \( b = 4 \), the density is 1/2 times the expression on the right-hand side of (1); for \( b = 3 \) and 5, the density is 3/4 times the expression on the right-hand side of (1).

It is of some interest to know a corresponding result for base 10. By applying an argument similar to what we will use for \( b = 4 \) in Theorem 1, it can be shown that there are infinitely many squarefree numbers which consist only of the digits 0, 1, and 2. In fact, if \( d_1, d_2, \) and \( d_3 \) are any three distinct digits not equal to 0, 4, and 8 in some order, then there are infinitely many squarefree numbers \( m \) in base 10 with each digit of \( m \) being either \( d_1, d_2, \) or \( d_3 \). We will not address this issue further here.

Our second theorem concerns squarefree polynomials in \( S \) (polynomials without any roots having multiplicity > 1). We shall see how to obtain the next result as a fairly direct consequence of our approach to establishing Theorem 1.

**Theorem 2.** Almost all polynomials in \( S \) are squarefree. In other words,

\[
\lim_{n \to \infty} \frac{|\{f(x) \in S_n: f(x) \text{ is squarefree}\}|}{2^n} = 1.
\]

In the next section, we give a proof of Theorem 1 for the case \( b = 3 \). In the process, we will establish some preliminaries for the cases \( b = 4 \) and 5. The remainder of the proof of Theorem 1 is given in Section 3. In Section 4, we will establish Theorem 2 using a lemma (Lemma 9) which aided in the proof of Theorem 1.

2. Some preliminaries and the case \( b = 3 \). Let \( n \) be a positive integer. For integers \( b \) and \( m \) with \( m \geq 2 \), we define \( t(n) = t(n, m, b) \) as the number of \( f(x) \in S_n \) for which \( m \) divides \( f(b) \). We begin with an estimate for \( t(n) \). Suppose first that \( m \) and \( b \) are integers which are not relatively prime. Then there is a prime \( p \) which divides both \( m \) and \( b \). Observe that
for every \( f(x) \in S_n \), we have \( f(b) \equiv 1 \pmod{p} \). Hence, for every \( f(x) \in S_n \), \( m \) does not divide \( f(b) \), and we deduce that \( t(n) = 0 \). The next lemma deals with the remaining situation where \( m \) and \( b \) are relatively prime integers.

**Lemma 1.** Let \( m \) and \( b \) be relatively prime integers with \( m \geq 2 \). Then

\[
t(n) = \frac{2^n}{m} (1 + o(1))
\]
as \( n \) approaches infinity.

**Proof.** Since

\[
\sum_{j=0}^{m-1} e^{2\pi iaj/m} = \begin{cases} m & \text{if } m \mid a, \\ 0 & \text{otherwise}, \end{cases}
\]
we obtain

\[
t(n) = \frac{1}{m} \sum_{f(x) \in S_n} \sum_{j=0}^{m-1} e^{2\pi if(b)j/m} = \frac{1}{m} \sum_{j=0}^{m-1} \sum_{f(x) \in S_n} e^{2\pi if(b)j/m}.
\]

On the other hand, from the definition of \( S_n \), we have

\[
\sum_{f(x) \in S_n} e^{2\pi if(b)j/m} = e^{2\pi ij/m} \prod_{k=1}^{n} (1 + e^{2\pi ib^k j/m}).
\]

Observe that when \( j = 0 \), the right-hand side is \( 2^n \). Hence,

\[
t(n) = \frac{2^n}{m} + E,
\]
where

\[
E = \frac{1}{m} \sum_{j=1}^{m-1} e^{2\pi ij/m} \prod_{k=1}^{n} (1 + e^{2\pi ib^k j/m}).
\]

It remains to show that \( E = o(2^n) \).

For each \( j \in \{1, \ldots, m-1\} \), we rewrite the absolute value of the product above as

\[
\left| \prod_{k=1}^{n} (1 + e^{2\pi ib^k j/m}) \right| = \left| \prod_{k=1}^{n} e^{\pi ib^k j/m} \right| \left| \prod_{k=1}^{n} (e^{\pi ib^k j/m} + e^{-\pi ib^k j/m}) \right|
\]

\[
= 2^n \prod_{k=1}^{n} |\cos(\pi b^k j/m)|.
\]

Since \( m \) and \( b \) are relatively prime and \( 1 \leq j \leq m - 1 \), the expression \( b^k j/m \) is a rational number which differs from an integer by at least \( 1/m \). Therefore,

\[
|\cos(\pi b^k j/m)| \leq |\cos(\pi/m)|.
\]
Since \( m \geq 2 \), this last expression is \(< 1 \). We obtain

\[
|E| \leq \frac{1}{m} \sum_{j=1}^{m-1} \left| \prod_{k=1}^{n} \left(1 + e^{2\pi i b^k j / m} \right) \right|
\]

\[
= \frac{2^n}{m} \sum_{j=1}^{m-1} \prod_{k=1}^{n} |\cos(\pi b^k j / m)| \leq 2^n |\cos(\pi / m)|^n,
\]

and the lemma easily follows.

**Lemma 2.** Let \( b \) be a positive integer, and let \( B \) be a real number \( > 0 \). Denote by \( S(B, n) \) the number of \( f(x) \in S_n \) such that \( f(b) \) is not divisible by \( p^2 \) for every prime \( p \leq B \). Then

\[
S(B, n) = 2^n \prod_{p \leq B, p \nmid b} \left(1 - \frac{1}{p^2}\right) + o(2^n).
\]

Lemma 2 follows from Lemma 1 by an easy sieve argument and we omit the details. Observe that

\[
\prod_{p \leq B, p \nmid b} \left(1 - \frac{1}{p^2}\right) = \prod_{p \mid b} \left(1 - \frac{1}{p^2}\right) (1 + O(1/B))
\]

\[
= \frac{6}{\pi^2} \prod_{p \mid b} \left(1 - \frac{1}{p^2}\right)^{-1} (1 + O(1/B)).
\]

Fix \( \varepsilon > 0 \). By choosing \( B \) sufficiently large and then choosing \( n \) sufficiently large, we deduce from Lemma 2 that \( S(B, n) \) differs from

\[
\frac{6 \cdot 2^n}{\pi^2} \prod_{p \mid b} \left(1 - \frac{1}{p^2}\right)^{-1}
\]

by \( \leq \varepsilon 2^n \). Thus, to prove Theorem 1, it suffices to show that the number of \( f(x) \in S_n \) such that \( f(b) \) is divisible by \( p^2 \) for some prime \( p > B \) is \( \leq \varepsilon 2^n \). For such an estimate we may suppose that \( B \) is arbitrarily large; more specifically, we can take \( B \geq B_0 \), where \( B_0 \) is an arbitrary constant depending only on \( \varepsilon \). The proof of Theorem 1 for the case \( b = 3 \) therefore follows from the following lemma.

**Lemma 3.** Let \( \varepsilon > 0 \), and let \( B \) be sufficiently large. Then there are \( \leq \varepsilon 2^n \) polynomials \( f(x) \in S_n \) for which there exists an integer \( d > B \) such that \( d^2 \mid f(3) \).

**Proof.** Let \( d \) be an integer \( > B \). Let \( r \) be the positive integer satisfying

\[
3^{r/2} < d \leq 3^{(r+1)/2}.
\]
We fix \( \varepsilon_r, \varepsilon_{r+1}, \ldots, \varepsilon_n \in \{0, 1\} \) arbitrarily and consider \( f(x) = \sum_{j=0}^{n} \varepsilon_j x^j \in S_n \). Observe that for any choice of \( \varepsilon_0, \varepsilon_1, \ldots, \varepsilon_{r-1} \in \{0, 1\} \), we have

\[
0 \leq \sum_{j=0}^{r-1} \varepsilon_j 3^j < d^2.
\]

Also, for distinct choices of the \( r \)-tuple \( (\varepsilon_0, \varepsilon_1, \ldots, \varepsilon_{r-1}) \) with each \( \varepsilon_j \in \{0, 1\} \), the numbers \( \sum_{j=0}^{r-1} \varepsilon_j 3^j \) are distinct; hence, they are distinct modulo \( d^2 \). We deduce that with \( \varepsilon_r, \varepsilon_{r+1}, \ldots, \varepsilon_n \in \{0, 1\} \) fixed, there is at most one choice of \( (\varepsilon_0, \varepsilon_1, \ldots, \varepsilon_{r-1}) \) such that \( f(3) \) is divisible by \( d^2 \). It follows that there are at most \( 2^{n-r+1} \) choices for \( f(x) \in S_n \) such that \( f(3) \) is divisible by \( d^2 \). The inequality \( 3^{(r+1)/2} \geq d > B \) implies that \( r \) is large. Hence,

\[
2^{n-r+1} = 2^{n+1}2^{-r} = 2^{n+1}(3^{r/2})^{-2 \log 2 / \log 3} \\
\leq 2^{n+1}(3^{(r+1)/2})^{-5/4} \leq 2^{n+1}d^{-5/4}.
\]

We deduce that the number of \( f(x) \in S_n \) such that \( f(3) \) is divisible by \( d^2 \) for some integer \( d > B \) is

\[
\leq 2^{n+1} \sum_{d>B} d^{-5/4}.
\]

Since \( B \) is sufficiently large and \( \sum_{d=1}^{\infty} d^{-5/4} \) converges, we deduce that this last expression is \( \leq \varepsilon 2^n \), completing the proof of the lemma. \( \blacksquare \)

3. The cases \( b = 4 \) and \( b = 5 \). In this section, we complete the proof of Theorem 1. We will improve on the argument given for Lemma 3 to obtain the desired result. We note that the work in this section allows us also to handle the case \( b = 3 \) here, but we have chosen to indicate the proof of the case \( b = 3 \) separately in the previous section partially because of its simplicity and partially because the case \( b = 3 \) of Theorem 1 by itself can be used to obtain Theorem 2 (see Section 4).

As in the previous section, we fix \( \varepsilon > 0 \) and consider \( B \) to be sufficiently large. Analogous to Lemma 3, we want to show for \( b = 4 \) and \( b = 5 \) that the number of \( f(x) \in S_n \) such that \( f(b) \) is divisible by \( d^2 \) for some \( d > B \) is \( \leq \varepsilon 2^n \).

For \( b \geq 3 \), we define

\[
S(b) = \left\{ \sum_{j=0}^{\infty} \varepsilon_j b^j : \varepsilon_j \in \{0, 1\}, \text{ all but finitely many } \varepsilon_j \text{ are } 0 \right\}
\]
For $r, b, u$,

Thus, the conditions $\gcd(b, u) = 4$; in particular, for the case $b = 5$, we will need a more intricate estimate for the case $b \nmid t$. The lemma which is a preliminary bound on $|X(r, t)|$.

**Lemma 4.** Let $b \geq 3$, $r \geq 2$, and $t \geq 1$ be integers. Then

$$|X(r, t)| \leq 3^{r+1}b^2.$$  

**Proof.** For any positive integers $m$ and $s$, $m$ is in $S'$ if and only if $b^s m$ is in $S'$. Thus, we may suppose that $b \nmid t$, and we do so. We may also suppose that $|X(r, t)| \neq 0$. Let $u$ be in $X(r, t)$. Then $tu^2$ is in $S'$. By the definition of $S'$, an element of $S'$ is either relatively prime to $b$ or it is divisible by $b$. Thus, the conditions $\gcd(b, u) = 1$ and $tu^2 \in S'$ imply $\gcd(b, t) = 1$.

We write

$$tu^2 = \sum_{k=0}^{\infty} \alpha_k b^k,$$

where each $\alpha_k = \alpha_k(u)$ is in $\{-1, 0, 1\}$. There are $3^{r+1}b^2$ different values for the $(r+2)$-tuple $(u', \alpha'_0, \alpha'_1, \ldots, \alpha'_r)$ where $u'$ is a non-negative integer $< b^2$ and $\alpha'_k \in \{-1, 0, 1\}$ for $k \in \{0, 1, \ldots, r\}$. Consider a fixed such $(r+2)$-tuple. The lemma will follow if we can show that there is at most one $u \in X(r, t)$ for which $u \equiv u' \pmod{b^2}$ and $\alpha_k(u) = \alpha'_k$ for every $k \in \{0, 1, \ldots, r\}$.

Let $u$ and $v$ be in $X(r, t)$ with $u \equiv v \pmod{b^2}$ and $\alpha_k(u) = \alpha_k(v)$ for every $k \in \{0, 1, \ldots, r\}$. We want to show that $u = v$. Let $p$ be a prime divisor of $b$. Then $\gcd(b, u) = 1$ implies $p \nmid u$. Since $\gcd(u - v, u + v) = \gcd(u - v, 2u)$, we deduce that if $p$ divides both $u - v$ and $u + v$, then $p = 2$. Also, $u \equiv v \pmod{b^2}$ implies $p^2 \mid (u - v)$ so that in the case $p = 2$, we have $4 \mid (u + v)$. Since $\gcd(b, t) = 1$, it follows that $\gcd(b^r+1, t(u + v))$ is either 1 or 2 and, hence, divides $b$. The condition $\alpha_k(u) = \alpha_k(v)$ for every $k \in \{0, 1, \ldots, r\}$ implies $b^r+1 \mid (tu^2 - tv^2)$. We deduce $b^r \mid (u - v)$. The conclusion $u = v$ now follows since $u$ and $v$ are positive integers $< b^r$. 

**Lemma 5.** Let $j$ and $s$ be positive integers. Let $K$ be a set of $s$-tuples $(\kappa_1, \ldots, \kappa_s)$ satisfying the two conditions:

(i) For each $i \in \{1, \ldots, s\}$, $\kappa_i \in \{1, 2, 3\}$.
(ii) For each \( t \in \{j + 1, j + 2, \ldots, s\} \), if \( \kappa_{i-t} \in \{2, 3\} \), then \( \kappa_i \in \{1, 2\} \). Then

\[
|K| \leq \left( \frac{3}{1 + \sqrt{2}} \right)^j (1 + \sqrt{2})^s.
\]

**Proof.** For each \( t \in \{1, \ldots, j\} \), consider the elements \((\kappa_1, \ldots, \kappa_s)\) of \( K \) and define \( K_t \) as the set of \([(s - t + j)/j\)-tuples \((\kappa_i, \kappa_{i+j}, \ldots, \kappa_{(s-t+j)/j}+t)\). Thus, \( |K| \leq \prod_{t=1}^j |K_t| \). Also, observe that the number of components in each element of \( K \) is the sum over \( t \) of the number of components in each element of \( K_t \). In other words,

\[
s = \sum_{t=1}^j \left[ \frac{s - t + j}{j} \right].
\]

Fixing \( t \in \{1, \ldots, j\} \), we consider the elements \((\psi_1, \ldots, \psi_{(s-t+j)/j})\) of \( K_t \). For each \( i \in \{1, \ldots, [(s - t + j)/j]\} \), we define \( N_i \) as the number of different choices for \( \psi_1, \ldots, \psi_i \) which arise. In other words, \( N_i \) is the number of \( i \)-tuples \((\psi_1, \ldots, \psi_i)\) obtained from the first \( i \) components of the elements of \( K_t \). Thus, \( |K_t| = N_{[(s-t+j)/j]} \). By condition (i), \( N_1 \leq 3 \). By conditions (i) and (ii), \( N_2 \leq 7 \) (there are \( \leq 3 \) choices for \((\psi_1, \psi_2)\) with \( \psi_1 = 1 \) and \( \leq 4 \) choices for \((\psi_1, \psi_2)\) with \( \psi_1 \in \{2, 3\} \)). Fix \( i \in \{3, 4, \ldots, [(s-t+j)/j]\} \). Let \( M \) be the number of \((i-1)\)-tuples \((\psi_1, \ldots, \psi_{i-1})\) with \( \psi_{i-1} = 1 \). Observe that \( M \leq N_{i-2} \). By condition (i), there are \( \leq 3M \) possible \( i \)-tuples \((\psi_1, \ldots, \psi_i)\) with \( \psi_{i-1} = 1 \). On the other hand, by condition (ii), there are \( \leq 2(N_{i-1-M} \) possible \( i \)-tuples \((\psi_1, \ldots, \psi_i)\) with \( \psi_{i-1} \in \{2, 3\} \). Therefore,

\[
N_i \leq 3M + 2(N_{i-1-M} = 2N_{i-1} + M \leq 2N_{i-1} + N_{i-2}.
\]

Recall that \( N_1 \leq 3 \) and \( N_2 \leq 7 \). An easy induction argument now gives

\[
N_i \leq 3(1 + \sqrt{2})^{i-1}.
\]

Thus,

\[
|K_t| = N_{[(s-t+j)/j]} \leq 3(1 + \sqrt{2})^{[(s-t+j)/j]} = \left( \frac{3}{1 + \sqrt{2}} \right)^{(1 + \sqrt{2})^{[(s-t+j)/j]}}.
\]

The lemma now follows from \( |K| \leq \prod_{t=1}^j |K_t| \) and (2). ■

**Lemma 6.** Let \( b \) be an odd integer \( \geq 5 \), and let \( r \) and \( j \) be positive integers with \( j \leq r \). Let \( a \) and \( t \) be positive integers and suppose that \( b^j \parallel a \). Then the number of positive integers \( u < b^r \) with \( \gcd(b, u) = 1 \) and such that both \( tu^2 \) and \( t(u + a)^2 \) are in \( S' \) is \( \leq (b-1)3^j(1 + \sqrt{2})^{r-j} \).

**Proof.** As in the proof of Lemma 4, we may suppose that \( \gcd(b, t) = 1 \) and do so. Let \( u \) be as in the statement of the lemma. Let

\[
D(u) = t(u + a)^2 - tu^2 = ta(2u + a).
\]
Since \( tu^2 \) and \( t(u+a)^2 \) are in \( S' \), we have

\[
(3) \quad tu^2 = \sum_{k=0}^{\infty} \alpha_k b^k \quad \text{and} \quad t(u+a)^2 = \sum_{k=0}^{\infty} \beta_k b^k
\]

for some integers \( \alpha_k \) and \( \beta_k \) in \( \{-1, 0, 1\} \). We write

\[
(4) \quad u = \sum_{k=0}^{r-1} u_k b^k \quad \text{and} \quad D(u) = \sum_{k=0}^{\infty} d_k b^k;
\]

where, for each non-negative integer \( k \), \( u_k \in [0, b-1] \) and

\[
(5) \quad d_k = \beta_k - \alpha_k \in [-2, 2].
\]

Note that since \( b \geq 5 \), \( D(u) \) has a unique representation as in (4) with \( d_k \in [-2, 2] \). Suppose now that \( v \) is a positive integer \( < b^r \) with \( v \neq u \) and \( \gcd(b, v) = 1 \) and such that both \( tv^2 \) and \( t(v+a)^2 \) are in \( S' \). Let \( l \) be the non-negative integer satisfying \( b^l \parallel (v-u) \). Then \( D(v) - D(u) = 2ta(v-u) \) so that

\[ b^{l+j} \parallel (D(v) - D(u)). \]

Viewing the numbers \( u_0, u_1, \ldots, u_{l-1} \) in (4) as fixed, we deduce that the numbers \( d_0, d_1, \ldots, d_{l+j-1} \) are uniquely determined. Furthermore, the number \( u_l \) uniquely determines the value of \( d_{l+j} \) and different values of \( u_l \) lead to different values of \( d_{l+j} \). In particular, there is at most one choice of \( u_l \) which leads to \( d_{l+j} = 0 \). We refer to such a choice of \( u_l \) as “nice”.

We keep the notation above and still view \( u_0, u_1, \ldots, u_{l-1} \) as fixed. Suppose that \( l \geq 1 \). Since \( b \) is an odd integer relatively prime to \( tu \), we obtain that \( \gcd(b, t(u+v)) = 1 \) so that \( b^l \parallel (vt^2 - tu^2) \). Hence, the numbers \( \alpha_0, \alpha_1, \ldots, \alpha_{l-1} \) in (3) are uniquely determined. Different values of \( u_l \) lead to different values of \( \alpha_l \). We are interested only in \( u \) for which \( tu^2 \in S' \) so that \( \alpha_l \in \{-1, 0, 1\} \). Therefore, there are at most 3 different values of \( u_l \) such that \( tu^2 \in S' \).

Since \( \alpha_l \) and \( \beta_l \) are in \( \{-1, 0, 1\} \), for each \( d_l \in \{-2, -1, 0, 1, 2\} \), there are at most 3 \( -|d_l| \) values of \( \alpha_l \) such that (5) holds. In particular, we deduce that if \( l \geq j \) and \( u_{l-j} \) is not nice (so that \( d_l \neq 0 \)), then there are at most two values of \( \alpha_l \), and hence at most two values of \( u_l \), for which \( tu^2 \) and \( t(u+a)^2 \) are both in \( S' \).

Since \( b \nmid u \), there are at most \( b - 1 \) choices for \( u_0 \) in (4). Fix \( u_0 \) and consider the choices for \( u_1, \ldots, u_{r-1} \) as in (4) with \( u \) as in the lemma. For \( l \in \{1, \ldots, r-1\} \) and for any given \( u_1, \ldots, u_{l-1} \), there are at most 3 different values of \( u_l \), say \( \gamma_i = \gamma_i(u_0, u_1, \ldots, u_{l-1}) \) where \( i \) is a positive integer \( \leq 3 \). At most one such \( u_l \) is nice, and if such a choice of \( u_l \) exists we can suppose that it is \( \gamma_1 \) and do so. We define \( \phi_l(u_l) = i \), where \( i \in \{1, 2, 3\} \) with \( u_l = \gamma_i \). Observe that \( u \) in (4) is uniquely determined by the value of
(\phi_1(u_1), \ldots, \phi_{r-1}(u_{r-1})) (where we are still viewing \(u_0\) as fixed). Also, if \(l \in \{j+1, j+2, \ldots, r-1\}\) and \(\phi_{l-j}(u_{l-j}) \in \{2, 3\}\) (so that \(u_{l-j}\) is not nice), then \(\phi_l(u_l) \leq 2\). Thus, the set of \((r-1)\)-tuples \((\phi_1(u_1), \ldots, \phi_{r-1}(u_{r-1}))\) satisfies the conditions of the set \(K\) in Lemma 5 with \(s = r - 1\). Recalling that there are \(\leq b - 1\) choices for the value of \(u_0\), we deduce that the number of \(u < b^r\) with \(\gcd(b, u) = 1\) and such that both \(tu^2\) and \(t(u + a)^2\) are in \(S'\) is

\[
\leq (b - 1) \left( \frac{3}{1 + \sqrt{2}} \right)^j (1 + \sqrt{2})^{r-1} < (b - 1)3^j(1 + \sqrt{2})^{r-j},
\]

establishing the lemma. ■

**Lemma 7.** Let \(b\) be a positive integer \(\geq 3\). Let \(r\) and \(l\) be positive integers with \(1 \leq l \leq r\). Let \(t\) be a positive integer. Then there exist \(3^{r-l+2}\) intervals each of length \(< 2b^l\) with the union of these intervals containing all numbers \(u\) for which \(b^{r-1} \leq u < b^r\) and \(tu^2 \in S'\).

**Proof.** Let \(s\) be the positive integer satisfying

\[
\frac{b^{s-1}}{b-1} < t \leq \frac{b^s}{b-1}.
\]

For \(u < b^r\) and \(tu^2 \in S'\), we obtain

\[
tu^2 = \sum_{k=0}^{2r+s-1} \alpha_k b^k \quad \text{for some } \alpha_k \in \{-1, 0, 1\}.
\]

Fix \(\alpha_k\) for \(r + s + l - 2 \leq k \leq 2r + s - 1\). Let

\[
\alpha = \sum_{k=r+s+l-2}^{2r+s-1} \alpha_k b^k - \sum_{k=0}^{r+s+l-3} b^k \quad \text{and} \quad \beta = \sum_{k=r+s+l-2}^{2r+s-1} \alpha_k b^k + \sum_{k=0}^{r+s+l-3} b^k.
\]

For \(b^{r-1} \leq u < b^r\) and \(tu^2 \in S'\), we deduce that \(tu^2\) is in some such \([\alpha, \beta]\) so that \(u \in [\gamma, \delta]\), where

\[
[\gamma, \delta] = [\sqrt{\alpha/t}, \sqrt{\beta/t}] \cap [b^{r-1}, b^r].
\]

Observe that

\[
\beta - \alpha = 2 \sum_{k=0}^{r+s+l-3} b^k < \frac{2b^{r+s+l-2}}{b-1}.
\]

Therefore,

\[
\delta - \gamma \leq \sqrt{\beta/t} - \sqrt{\alpha/t} = \frac{\beta - \alpha}{t(\sqrt{\beta/t} + \sqrt{\alpha/t})}
\]

\[
< \frac{\beta - \alpha}{t\gamma} \leq \frac{\beta - \alpha}{tb^{r-1}} < \frac{2b^{r+s+l-2}/(b-1)}{b^{r-s-2}/(b-1)} = 2b^l.
\]
Hence, the $3^{r-l+2}$ choices for $\alpha_{r+1} \ldots, \alpha_{2r-1}$, each in $\{-1, 0, 1\}$, lead to $3^{r-l+2}$ intervals $[\gamma, \delta]$ of length $< 2b^l$ satisfying the conditions of the lemma.

Since $b \geq 3$, it is not difficult to check that the intervals in the proof of Lemma 7 above are disjoint. On the other hand, it is already clear in the statement of Lemma 7 that we may consider these intervals to be disjoint.

**Lemma 8.** Let $b$ be an odd integer $\geq 5$. Let $r$ and $t$ be positive integers. Then
\[
|X(r, t)| \ll \exp \left( \frac{\log 3(\log b + \log(1 + \sqrt{2}))r}{\log(3b)} \right),
\]
where the implied constant depends on $b$ but not on $r$ or $t$.

**Proof.** Consider an arbitrary positive integer $l \leq r$. By Lemma 7, $X(r, t)$ is contained in the union of $3^{r-l+2}$ disjoint intervals $[\gamma, \delta]$, with $1 \leq i \leq 3^{r-l+2}$, where each interval is of length $< 2b^l$. For each $i \in \{1, \ldots, 3^{r-l+2}\}$ and $k \in \{1, \ldots, b-1\}$, we set
\[
X_{i,k}(r, t) = \{u \in X(r, t) : u \in [\gamma, \delta] \text{ and } u \equiv k \pmod{b}\}.
\]
Let $n_{i,k} = |X_{i,k}(r, t)|$. Then
\[
\sum_{i=1}^{3^{r-l+2}} \sum_{k=1}^{b-1} \frac{n_{i,k}(n_{i,k} - 1)}{2} = \sum_{i=1}^{3^{r-l+2}} \sum_{k=1}^{3^{r-l+2}} |\{(u, v) : u \in X_{i,k}(r, t), v \in X_{i,k}(r, t), \text{ and } u < v\}|
\]
\[
= \sum_{1 \leq a < 2b^l} \sum_{i=1}^{b/a} \sum_{k=1}^{3^{r-l+2}} |\{(u, v) : u \in X_{i,k}(r, t), v \in X_{i,k}(r, t), \text{ and } v - u = a\}|
\]
\[
\leq \sum_{1 \leq a < 2b^l} |\{(u, v) : u \in X(r, t), v \in X(r, t), \text{ and } v - u = a\}|.
\]
From Lemma 6, we now deduce that
\[
\sum_{i=1}^{3^{r-l+2}} \sum_{k=1}^{b-1} \frac{n_{i,k}(n_{i,k} - 1)}{2} \leq \sum_{j=1}^{l} \sum_{1 \leq a < 2b^l \atop b^j \parallel a} (b-1)3^j(1 + \sqrt{2})^{r-j}
\]
\[
\leq \sum_{j=1}^{l} 2b^{l-j}(b-1)3^j(1 + \sqrt{2})^{r-j} \ll b^l(1 + \sqrt{2})^r.
\]
Therefore,
\[ |X(r, t)| = \sum_{i=1}^{3^{r-l+2}} \sum_{k=1}^{b-1} n_{i,k} \leq \sum_{i=1}^{3^{r-l+2}} \sum_{k=1}^{b-1} \left( 1 + \frac{n_{i,k}(n_{i,k} - 1)}{2} \right) \]
\[ = \sum_{i=1}^{3^{r-l+2}} \sum_{k=1}^{b-1} 1 + \sum_{i=1}^{3^{r-l+2}} \sum_{k=1}^{b-1} \frac{n_{i,k}(n_{i,k} - 1)}{2} \ll 3^{r-l} + b^l(1 + \sqrt{2})^r. \]

We choose
\[ l = \left\lceil \frac{(\log 3 - \log(1 + \sqrt{2}) r}{\log(3b)} \right\rceil + 1 \]
to obtain the lemma. ■

**Lemma 9.** Let \( b = 4 \) or 5. Let \( \varepsilon > 0 \), and let \( B = B(\varepsilon) \) be sufficiently large. Then the number of \( f(x) \in S_n \) such that \( f(b) \) is divisible by \( d^2 \) for some integer \( d > B \) is \( \leq \varepsilon 2^n \).

**Proof.** Since \( B \) is sufficiently large, the number of \( f(x) \in S_n \) as in the lemma is 0 unless \( n \) is also large. We therefore consider \( n \) large. Let \( r \) be a positive integer for which \( b^r > B \). We consider the integers \( d \) such that \( b^{-1} \leq d < b^r \). For \( f(x) \in S_n \), we have \( 0 < f(b) \leq b^{n+1} \) so that if \( f(b) \) is divisible by \( d^2 \) (which is \( \geq b^{2r-2} \)), then \( r \leq (n+3)/2 \). We therefore suppose, as we may, that \( r \leq (n+3)/2 \).

Recall that each \( f(x) \in S_n \) has constant term 1 so that if \( f(b) \) is divisible by \( d^2 \), then \( \gcd(b, d) = 1 \). If \( f(b) = td^2 \), then we also have \( 1 \leq t = f(b)/d^2 \leq b^{n-2r+3} \) so that \( d \in X(r, t) \) for some positive integer \( t \leq b^{n-2r+3} \). We use Lemmas 4 and 8 to deduce that the number of \( f(x) \in S_n \) for which there exists a \( d \in [b^{-1}, b^r] \) such that \( d^2 | f(b) \) is

\[ \sum_{i=1}^{b^{n-2r+3}} |X(r, t)| \leq \left\{ \begin{array}{ll}
4^{n-2r}3^r & \text{for } b = 4, \\
5^{n-2r} \exp \left( \frac{\log 3(\log 5 + \log(1 + \sqrt{2}) r)}{\log 15} \right) & \text{for } b = 5.
\end{array} \right. \]

In either case, if \( r > n/(2.4) \), the above expression on the right is easily \( \ll 2^n/(nB) \). We restrict our attention now to \( r \leq n/(2.4) \). We note that our method for obtaining this bound on \( r \) is not the best possible, and it would be easy to replace 2.4 with a larger number; however, 2.4 will be sufficient for what follows.

Let \( s \) denote a positive integer \( \leq n-2r \). We consider \( f(x) = \sum_{j=0}^{n} \varepsilon_j x^j \in S_n \) with \( \varepsilon_{2r+s-2}, \varepsilon_{2r+s-1}, \ldots, \varepsilon_n \) fixed elements from \( \{0, 1\} \). Thus, we obtain \( 2^{2r+s-3} \) different values of \( f(b) \). Let \( N(d) \) denote the number of different \((2r+s-3)\)-tuples \((\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_{2r+s-3})\), with each \( \varepsilon_j \in \{0, 1\} \), such that \( d^2 | f(b) \). Suppose \( N(d) \geq 1 \). Consider the \( f(x) \) counted by \( N(d) \), and let \( f_1(x) \) denote the \( f(x) \) which minimizes the value of \( f(b) \). Then there are
Thus, there are at least \(N(d) - 1\) other \(f(x)\) counted by \(N(d)\) each having the property that \(d^2 \mid f(b)\). For each of these \(N(d) - 1\) different \(f(x)\), we obtain

\[0 < f(b) - f_1(b) \leq b^{2r+s-2} \leq d^2b^s.
\]

Thus, there are at least \(N(d) - 1\) different \(f(x) \in S_n\) (with \(\epsilon_{2r+s-2}, \epsilon_{2r+s-1}, \ldots, \epsilon_n\) fixed) such that \(f(b) - f_1(b) = td^2\) for some positive integer \(t \leq b^s\). Different choices for \(f(x)\) give different values for \(t\). We deduce that there are at least \(N(d) - 1\) different \(t \leq b^s\) for which \(d \in X(r, t)\).

With \(\epsilon_{2r+s-2}, \epsilon_{2r+s-1}, \ldots, \epsilon_n\) still fixed, we bound the number of \(f(x) \in S_n\) such that there is a \(d \in [b^{-1}, b^r]\) for which \(d^2 \mid f(b)\). This number is

\[
\leq \sum_{b^{-1} \leq d < b^r} N(d) = \sum_{b^{-1} \leq d < b^r} (N(d) - 1) + \sum_{b^{-1} \leq d < b^r} 1.
\]

From our comments above and from Lemmas 4 and 8, we deduce that

\[
\sum_{b^{-1} \leq d < b^r} (N(d) - 1) \leq \sum_{1 \leq t \leq b^r} \sum_{d \in X(r, t)} 1 = \sum_{1 \leq t \leq b^r} |X(r, t)|
\]

\[
\ll \begin{cases} 4^s3^r & \text{for } b = 4, \\ 5^s \exp \left( \frac{\log 3(\log 5 + \log(1 + \sqrt{2}))r}{\log 15} \right) & \text{for } b = 5. \end{cases}
\]

Also,

\[
\sum_{b^{-1} \leq d < b^r} 1 \leq b^r.
\]

Letting \(\epsilon_{2r+s-2}, \epsilon_{2r+s-1}, \ldots, \epsilon_n\) now vary, we deduce that the number of \(f(x) \in S_n\) such that there exists a \(d \in [b^{-1}, b^r]\) for which \(d^2 \mid f(b)\) is

\[
\ll 2^{n-2r-s}4^s3^r + 2^{n-2r-s}4^s & \text{for } b = 4,
\]

and

\[
\ll 2^{n-2r-s}5^s \exp \left( \frac{\log 3(\log 5 + \log(1 + \sqrt{2}))r}{\log 15} \right) + 2^{n-2r-s}5^s & \text{for } b = 5.
\]

In the case \(b = 4\), we choose

\[
s = \left[ \frac{r \log(4/3)}{\log 4} \right] + 1;
\]

and in the case \(b = 5\), we choose

\[
s = \left[ \frac{r \log 5}{\log 5} \log 5 + \log(1 + \sqrt{2})(\log 3) \right] + 1.
\]
It is easily checked that since \( 1 \leq r \leq n/(2^4) \), in either case the choice of \( s \) is a positive integer \( \leq n - 2r \). We deduce that the number of \( f(x) \in S_n \) such that \( f(b) \) is divisible by some \( d^2 \) with \( b^{r-1} \leq d < b^r \) is

\[
\ll 2^{n-2r-s}b^r \ll \begin{cases} 2^n \exp(-0.14r) & \text{for } b = 4, \\ 2^n \exp(-0.034r) & \text{for } b = 5. \end{cases}
\]

In either case, \( b = 4 \) or \( b = 5 \), since \( e^2 > b \), the above bound is \( \ll 2^n e^{-2r/100} \ll 2^n b^{-r/100} \).

Letting \( r \) vary over the positive integers for which \( b^r > B \), we easily deduce now that the number of \( f(x) \in S_n \) such that \( f(b) \) is divisible by \( d^2 \) for some \( d > B \) is \( \ll 2^n B^{-1/100} \). Since \( B \) is sufficiently large, the proof of the lemma is complete. ■

4. The proof of Theorem 2. Let \( R \) be a fixed real number \( \geq 1 \). We begin by estimating the number of \( f(x) \in S_n \) divisible by the square of a non-constant polynomial in \( \mathbb{Z}[x] \) of degree \( \leq R \). We will show that there are \( o(2^n) \) such \( f(x) \).

Odlyzko and Poonen [2] have obtained extensive results about the roots of polynomials in \( S_n \). For our purposes, it suffices to know that these roots are bounded in absolute value by 2 which is easily established as follows. Let \( f(x) \in S_n \), and write \( f(x) = \sum_{j=0}^m \varepsilon_j x^j \) where \( m \leq n \), \( \varepsilon_j \in \{0, 1\} \) for each \( j \), and \( \varepsilon_0 = \varepsilon_m = 1 \). If \( \alpha \in \mathbb{C} \) and \( |\alpha| \geq 2 \), then

\[
|f(\alpha)| \geq \left| \sum_{j=0}^m \varepsilon_j \alpha^j \right| \geq |\alpha|^m - \sum_{j=0}^{m-1} |\alpha|^j = |\alpha|^m - \frac{|\alpha|^m - 1}{|\alpha| - 1} = \frac{|\alpha|^{m+1} - 2|\alpha|^m + 1}{|\alpha| - 1} = \frac{(|\alpha| - 2)|\alpha|^m + 1}{|\alpha| - 1} > 0.
\]

Thus, \( f(\alpha) \neq 0 \), and we deduce that all roots of the polynomials in \( S_n \) necessarily have absolute value \( < 2 \).

Let \( g(x) \in \mathbb{Z}[x] \) of degree \( r \in [1, R] \), and suppose that \( g(x) \) is a factor of some polynomial in \( S_n \). It follows that the roots of \( g(x) \) have absolute value \( < 2 \). Also, since polynomials in \( S_n \) are monic, the leading coefficient of \( g(x) \) must be \( \pm 1 \). Since the degree of \( g(x) \) is \( \leq R \), it follows that each coefficient of \( g(x) \) has absolute value less than or equal to the product of \( 2^R \) (an upper bound on the absolute value of the product of the roots of \( g(x) \)) and \( 2^R \) (an upper bound on the number of combinations of \( r \leq R \) roots taken \( k \) at a time where \( k \in \{0, 1, \ldots, r\} \)). Since the absolute value of the coefficients of \( g(x) \) are bounded by \( 4^R \) and since \( g(x) \) has degree \( \leq R \), there are

\[
\leq (2 \cdot 4^R + 1)^{R+1}
\]

different possible values of \( g(x) \). To establish what we first set out to show,
it suffices then to deduce that for each such \( g(x) \), there are \( o(2^n) \) different possible \( f(x) \in S_n \) divisible by \( g(x)^2 \).

Fix \( g(x) \) as above. Suppose that \( f(x) = \sum_{j=0}^n \varepsilon_j x^j \in S_n \) is divisible by \( g(x)^2 \). We consider the set \( T_n(f(x)) \) consisting of the polynomials \( w(x) = \sum_{j=0}^n \varepsilon'_j x^j \in S_n \) where there is exactly one \( k \in \{1, \ldots, n\} \) for which \( \varepsilon'_k \neq \varepsilon_k \). In other words, \( w(x) = \sum_{j=0}^n \varepsilon'_j x^j \in T_n(f(x)) \) if and only if there is a \( k \in \{1, \ldots, n\} \) such that \( \varepsilon'_l = \varepsilon_l \) for every \( l \in \{0, 1, \ldots, n\} \) with \( l \neq k \) and \( \varepsilon'_k = 1 - \varepsilon_k \). Thus, \( |T_n(f(x))| = n \). Since \( f(x) \) is divisible by \( g(x)^2 \) and \( f(x) \) has constant term 1, it must be the case that \( g(x) \) is not divisible by \( x \). If \( w(x) = \sum_{j=0}^n \varepsilon'_j x^j \in T_n(f(x)) \) and \( k \in \{1, \ldots, n\} \) with \( \varepsilon'_k \neq \varepsilon_k \), then \( f(x) - w(x) = \pm x^k \) is not divisible by \( g(x)^2 \). We deduce that the elements of \( T_n(f(x)) \) are not divisible by \( g(x)^2 \).

Now, suppose that \( f_1(x) \) and \( f_2(x) \) are distinct polynomials in \( S_n \) each divisible by \( g(x)^2 \). We show that \( T_n(f_1(x)) \) and \( T_n(f_2(x)) \) are disjoint. If the sets were not disjoint, then there would be some \( w(x) \) which differs from each of \( f_1(x) \) and \( f_2(x) \) by a power of \( x \). By considering \( f_1(x) - f_2(x) \), it follows that for some \( k \) and \( l \) in \( \{1, \ldots, n\} \) with \( k > l \), \( x^k \pm x^l = x^l(x^{k-l} \pm 1) \) is divisible by \( g(x)^2 \). Since the roots of \( x^{k-l} \pm 1 \) are distinct and since \( g(x) \) is not divisible by \( x \), we deduce that \( g(x)^2 \) cannot divide \( x^l(x^{k-l} \pm 1) \). Hence, \( T_n(f_1(x)) \) and \( T_n(f_2(x)) \) are disjoint.

For each \( f(x) \in S_n \) divisible by \( g(x)^2 \), there correspond \( n \) polynomials, namely the elements of \( T_n(f(x)) \), which are not divisible by \( g(x)^2 \), and these \( n \) polynomials are different for different \( f(x) \). Thus, there are \( \leq 2^n/(n+1) \) polynomials in \( S_n \) divisible by \( g(x)^2 \). Hence, there are \( o(2^n) \) polynomials in \( S_n \) divisible by \( g(x)^2 \) and thus \( o(2^n) \) polynomials \( f(x) \in S_n \) which are divisible by the square of a polynomial of degree \( \leq R \).

Fix \( \varepsilon > 0 \). It suffices to show that if \( R \) is sufficiently large, then there are \( \leq \varepsilon 2^n \) polynomials \( f(x) \in S_n \) which are divisible by the square of a polynomial in \( \mathbb{Z}[x] \) of degree \( > R \). We will use Theorem 1 with \( b = 4 \) and the fact already established that the roots of the polynomials in \( S_n \) have absolute value \( < 2 \). We note, however, that the case \( b = 3 \) of Theorem 1 could be used instead of the case \( b = 4 \) if we use the fact that the roots of the polynomials in \( S_n \) have real parts \( < 1.5 \) (cf. [1] or [2]).

Let \( f(x) \in S_n \) with \( f(x) \) divisible by the square of a polynomial \( g(x) \in \mathbb{Z}[x] \) of degree \( r > R \). We may suppose that \( g(x) \) is monic (otherwise, replace \( g(x) \) with \(-g(x)\)). Then the roots of \( f(x) \) and hence \( g(x) \) have absolute value \( < 2 \). If \( \beta_1, \ldots, \beta_r \) denote the roots of \( g(x) \), then \( g(x) = \prod_{j=1}^r (x - \beta_j) \) and

\[
|g(4)| = \prod_{j=1}^r |4 - \beta_j| \geq 2^r > 2^R.
\]

Since \( f(x) \) is divisible by \( g(x)^2 \), we deduce that \( f(4) \) is divisible by \( d^2 \) for
some integer \( d > 2^R \). On the other hand, from Lemma 9 with \( b = 4 \), we deduce that for \( R \) sufficiently large, there are \( \leq \varepsilon 2^n \) such polynomials \( f(x) \in S_n \). Hence, Theorem 2 follows.

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