A note on integer polynomials with small integrals. II

A NOTE ON INTEGER POLYNOMIALS WITH SMALL INTEGRALS II

DANILO BAZZANELLA

ABSTRACT. The smart method of Gelfond–Shnirelman–Nair allows one to obtain in elementary way a lower bound for the prime counting function $\pi(x)$ in terms of integrals of suitable integer polynomials. In this paper we carry on the study of the properties of the sets of integer polynomials relevant for the method.

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1. INTRODUCTION

In 1851, Chebyshev [7] made the first step towards the Prime Number Theorem by proving that, given $\varepsilon > 0$,

$$(c_1 - \varepsilon)\frac{N}{\log N} \le \pi(N) \le (c_2 + \varepsilon)\frac{N}{\log N}$$

where $c_1 = \log(2^{1/2}3^{1/3}5^{1/5}/30^{1/30})$, $c_2 = 6c_1/5$ and N is sufficiently large. This result was proved using elementary approaches, i.e. without use of complex analysis and the Riemann zeta function. A survey of elementary methods in the study of the distribution of prime numbers may be found in Diamond [8].

In 1936 Gelfond and Shnirelman, see Gelfond's editorial remarks in the 1944 edition of Chebyshev's Collected Works [7, pag. 287-288], proposed a new elementary and clever method for deriving a lower bound for the prime counting functions $\pi(x)$ and $\psi(x)$. In 1982 the Gelfond-Shnirelman method was rediscovered and developed by Nair, see [10] and [11]. The method of Gelfond–Shnirelman–Nair allows one to obtain in elementary way a lower bound for $\pi(x)$ in terms of integrals of suitable integer polynomials and it is based on the fact that the least common multiple of the integers not greater than N, say d_N, satisfied

$$d_N \le \prod_{p \le N} p^{\log N/\log p},$$

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where p belongs to the set of prime numbers, which implies

$$\pi(N) \geq \frac{\log d_N}{\log N}. \tag{1}$$

Considering a polynomial of degree $N-1$ with integral coefficients

$$P(x) = \sum_{n=0}^{N-1} a_n x^n$$

and letting

$$I(P) = \int_0^1 P(x)\,\mathrm{d}x = \sum_{n=0}^{N-1} \frac{a_n}{n+1},$$

we note that $I(P)d_N$ is an integer, and hence if $I(P) \neq 0$ we have

$$d_N|I(P)| \geq 1$$

and then

$$d_N \geq \frac{1}{|I(P)|}.$$

From the above and (1) we get

$$\pi(N) \geq \frac{\log(1/|I(P)|)}{\log N}. \tag{2}$$

By the definition of $I(P)$, it follows that the small positive value of $|I(P)|$ is $1/d_N$ and it is reached if

$$\sum_{n=0}^{N-1} \frac{d_N}{n+1} a_n = \pm 1.$$

Since the integer coefficients $d_N, d_N/2, \ldots, d_N/N$ are relatively prime, we have that for all N there exists a polynomial of degree less than N such that $I(P) = 1/d_N$. This leads to define the following sets of polynomials.

Definition. *Let $N \geq 2$. We define*

$$Z_N = \{P(x) \in \mathbb{Z}[x], \deg(P) < N\},$$

$$R_N = \{P(x) \in \mathbb{Z}[x], \deg(P) < N, I(P) = 0\}$$

and

$$S_N = \{P(x) \in \mathbb{Z}[x], \deg(P) < N, I(P) = 1/d_N\},$$

where d_N denotes the least common multiple of the integers $1, 2, \ldots, N$.

It is simple to verify that, for every N, Z_N is a free $\mathbb{Z}$-module and R_N is a submodule of Z_N and then it is also free. S_N is the affine space of the integer polynomials with positive and minimal integral on $[0, 1]$.

In the precedent paper [3] we proved some results about the roots of polynomials of the sets S_N. In the present paper we carry on the study of the properties of the sets of integer polynomials relevant for the method.

2. Properties of the sets R_N

We start giving a theorem about the structure of the modules R_N.

Theorem 1. *A basis B_N of the module R_N can be constructed by adding to a basis B_{N-1} of the module R_{N-1} a suitable polynomial $q(x) \in R_N$. More precisely*

(1) *if N is a prime: $q(x) = 1 - Nx^{N-1}$;*
(2) *if N is a power of a prime: $q(x) = x^{n-1} - px^{N-1}$, where $N = p^k$ and $n = p^{k-1}$;*
(3) *otherwise: $q(x) = a_1 x^{n_1-1} + a_2 x^{n_2-1} - x^{N-1}$, where p_1 and p_2 are primes dividing N, a_1 and a_2 are such that $a_1p_1 + a_2p_2 = 1$, $n_1 = N/p_1$ and $n_2 = N/p_2$.*

Proof. Let N prime and $p(x) \in R_N$. Then we can write

$$p(x) = a_0 + a_1x + a_2x^2 + \cdots + a_{N-1}x^{N-1}$$

with

$$a_0 d_N + a_1\frac{d_N}{2} + a_2\frac{d_N}{3} + \cdots + a_{N-2}\frac{d_N}{N-1} + a_{N-1}\frac{d_N}{N} = 1.$$

Since N is a prime number we have that $d_N = Nd_{N-1}$ and then

$$N/d_N, N/\frac{d_N}{2}, N/\frac{d_N}{3}, \ldots N/\frac{d_N}{N-1}$$

and N does not divide d_N/N. From this it follows that a_{N-1}/N is an integer.

Now we define

$$r(x) = a_0 + a_1x + a_2x^2 + \cdots + a_{N-2}x^{N-2} + \frac{a_{N-1}}{N},$$

which implies

$$p(x) = r(x) + a_{N-1}x^{N-1} - \frac{a_{N-1}}{N} = r(x) - \frac{a_{N-1}}{N}\left(1 - Nx^{N-1}\right).$$

Then (1) is proved, since $r(x) \in R_{N-1}$.

To prove (2) we let $N = p^k$. In this case $d_N = p\, d_{N-1}$ and more precisely

$$d_N = \prod_{q \le N} q^{[\ln q/\ln N]} = p^k \prod_{q \le N, q \ne p} q^{[\ln q/\ln N]} = Nm,$$

where $(m, p) = 1$ and q runs over primes. From this follows that

$$p/d_N, p/\frac{d_N}{2}, p/\frac{d_N}{3}, \ldots p/\frac{d_N}{N-1}$$

and p does not divide d_N/N, hence a_{N-1}/p is an integer.

Now we define $n = p^{k-1}$ and

$$r(x) = a_0 + a_1x + a_2x^2 + \cdots + a_{N-2}x^{N-2} + \frac{a_{N-1}}{p}x^{n-1},$$

which implies

$$p(x) = r(x) + a_{N-1}x^{N-1} - \frac{a_{N-1}}{p}x^{n-1} = r(x) - \frac{a_{N-1}}{p}\left(x^{n-1} - px^{N-1}\right).$$

Then also (2) is proved, since $r(x) \in R_{N-1}$.

To prove (3) we observe that if N is neither prime nor power of a prime then there exist two primes $p_1 \neq p_2$ both dividing N. Let a_1 and a_2 integers such that $a_1p_1 + a_2p_2 = 1$, we define $n_1 = N/p_1$, $n_2 = N/p_2$ and

$$r(x) = a_0 + a_1x + a_2x^2 + \cdots + a_{N-2}x^{N-2} + a_1a_{N-1}x^{n_1-1} + a_2a_{N-1}x^{n_2-1}.$$

We conclude that

$$p(x) = r(x) - a_{N-1}\left(a_1x^{n_1-1} + a_2x^{n_2-1} - x^{N-1}\right).$$

and then the proof of the theorem is complete, since $r(x) \in R_{N-1}$. □

Using Theorem 1 we can fully describe the sets R_N. By the definition we have

$$R_2 = \{p(x) \in \mathbb{Z}[x], p(x) = a_0 + a_1x, 2a_0 + a_1 = 0\} = \{p(x) \in \mathbb{Z}[x], p(x) = a_0(1-2x), a_0 \in \mathbb{Z}\}.$$

Then a basis B_2 of the set R_2 is

$$B_2 = \{1 - 2x\}.$$

Using several times Theorem 1 we can get a basis B_N of the set R_N for many values of N:
$B_3 = \{1 - 2x, 1 - 3x^2\}$,
$B_4 = \{1 - 2x, 1 - 3x^2, -x + 2x^3\}$,
$B_5 = \{1 - 2x, 1 - 3x^2, -x + 2x^3, 1 - 5x^4\}$,
$B_6 = \{1 - 2x, 1 - 3x^2, -x + 2x^3, 1 - 5x^4, x(1 - x - x^4)\}$,
$B_7 = \{1 - 2x, 1 - 3x^2, -x + 2x^3, 1 - 5x^4, x(1 - x - x^4), 1 - 7x^6\}$,
$B_8 = \{1 - 2x, 1 - 3x^2, -x + 2x^3, 1 - 5x^4, x(1 - x - x^4), 1 - 7x^6, x^3 - 2x^7\}$,
$B_9 = \{1 - 2x, 1 - 3x^2, -x + 2x^3, 1 - 5x^4, x(1 - x - x^4), 1 - 7x^6, x^3 - 2x^7, x^2 - 3x^8\}, \ldots$

3. Properties of the sets S_N

To describe the sets S_N is much more complicated. Since S_N are affine spaces, we can write

$$S_N = \{\overline{p}(x) + r(x) : r(x) \in R_N\},$$

where $\overline{p}(x)$ is a fixed polynomial of S_N. For small values of N it is simple to find such a suitable polynomial

N	$\overline{p}(x)$	N	$\overline{p}(x)$
3	$x(1-x)$	14	$x^7(1-x)^4(2x-1)(-3+4x)$
4	$x^2(1-x)$	15	$x^7(1-x)^6(2x-1)$
5	$x^2(1-x)(2x-1)$	16	$x^8(1-x)^6(4-7x)$
6	$x^3(1-x)^2$	17	$x^8(1-x)^6(2x-1)(4-5x)$
7	$x^3(1-x)^2(2x-1)$	18	$x^9(1-x)^6(2x-1)(3-4x)$
8	$x^4(1-x)^2(2-3x)$	19	$x^9(1-x)^6(2x-1)^2(53-77x)$
9	$x^4(1-x)^3(2x-1)$	20	$x^{10}(1-x)^6(2x-1)^2(42-59x)$
10	$x^4(1-x)^3(2x-1)$	21	$x^{10}(1-x)^7(2x-1)^2(-2+3x)$
11	$x^5(1-x)^3(2x-1)(-4+5x)$	22	$x^{12}(1-x)^6(2x-1)^2(17-23x)$
12	$x^6(1-x)^3(2x-1)(-3+4x)$	23	$x^{12}(1-x)^7(2x-1)^2(-62+87x)$
13	$x^6(1-x)^4(2x-1)(-4+5x)$	24	$x^{12}(1-x)^7(2x-1)^3(-3+4x)$

Unfortunately it is very difficult to find out such a polynomial for a generic value of N. However we may provide some theorems about their factorization.

Theorem 2. *For every $N \geq 3$ there exists a polynomial $p(x) \in S_N$ such that $p(0) = p(1) = 0$, namely $p(x) = x(1-x)q(x)$ with $q(x) \in \mathbb{Z}[x]$.*

Proof. The list of polynomials given before shows that the theorem is true for $3 \leq N \leq 7$. Then we let $N \geq 8$ and $p(x) \in S_N$, that is

$$p(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_{N-1}x^{N-1}$$

and

$$a_0 d_N + a_1 \frac{d_N}{2} + a_2 \frac{d_N}{3} + a_3 \frac{d_N}{4} + \cdots + a_{N-2}\frac{d_N}{N-1} + a_{N-1}\frac{d_N}{N} = 1. \tag{3}$$

The Diophantine equation

$$a_3 \frac{d_N}{4} + a_4 \frac{d_N}{5} \cdots + a_{N-2}\frac{d_N}{N-1} + a_{N-1}\frac{d_N}{N} = 1$$

has an integer solution (a_3, a_4, a_{N-1}), since for $N \geq 8$ we have

$$\left(\frac{d_N}{4}, \frac{d_N}{5}, \ldots, \frac{d_N}{N-1}, \frac{d_N}{N}\right) = 1.$$

Setting $a_0 = 0$, $a_1 = 2(a_3 + a_4 + \cdots + q_{N-1})$ and $a_2 = -3(a_3 + a_4 + \cdots + q_{N-1})$ we have that $(a_0, a_1, a_2, \ldots, a_{N-1})$ is a solution of (3) and verify $p(0) = a_0 = 0$ and

$$p(1) = a_0 + a_1 + a_2 + \cdots + a_{N-1} = 0,$$

which concludes the proof of the theorem. □

At the cost of some complications we can prove a similar result also including the factor $(2x-1)$.

Theorem 3. *Let $N \geq 4$.*

(1) *If N is not a power of 2, then there exists a polynomial $p(x) \in S_N$ such that $p(0) = p(1) = p(1/2) = 0$, namely such that $p(x) = x(1-x)(2x-1)q(x)$ with $q(x) \in \mathbb{Z}[x]$;*
(2) *If N is a power of 2, then there not exists a polynomial $p(x) \in S_N$ such that $(2x-1)/p(x)$.*

Proof. Let $p(x) = (2x-1)(b_0 + b_1 x + b_2 x^2 + \cdots + a_{N-2}x^{N-2})$. The condition

$$\int_0^1 p(x)\,\mathrm{d}x = \frac{1}{d_N}$$

is equivalent to

$$\sum_{k=1}^{N-2} \frac{d_N\ k}{(k+1)(k+2)} b_k = 1. \tag{4}$$

If N is a power of 2, then all the coefficients

$$\frac{d_N\ k}{(k+1)(k+2)}$$

are even and thus the equation (4) has no solutions, therefore there not exists a polynomial $p(x) \in S_N$ such that $(2x-1)/p(x)$.

The list of polynomials given before shows that (1) is true for $4 \leq N \leq 24$ and then we need only to consider the case $N \geq 25$. If N is not a power of 2, then we are able to prove that the coefficients

$$\frac{d_N\ k}{(k+1)(k+2)}$$

are relatively prime. In order to prove the coprimality, we suppose on the contrary that there exists a prime p dividing

$$\frac{d_N\ k}{(k+1)(k+2)}$$

for every $k = 1, 2, \ldots, N-2$. Let $H = p^j$, with $j = \max\{i : p^i \leq N\}$ and observe that p does not divide d_N/H. Then at least one of the two coefficients

$$\frac{d_N\ (H-1)}{H(H+1)} \text{ and } \frac{d_N\ (H-2)}{(H-1)H},$$

is not divisible by p, a contradiction. By the coprimality of the coefficients of the Diophantine equation (4) follows that there exists $p(x) \in S_N$ such that $(2x-1)/p(x)$.

To have also the factors x and $(1-x)$ it is sufficent to note that the integer H defined above is greater than 7, since $N \geq 25$, and then there exists a solution $(b_4, b_5, \ldots, b_{N-2})$ of the Diophantine equation

$$\sum_{k=4}^{N-2} \frac{d_N\ k}{(k+1)(k+2)} b_k = 1. \tag{5}$$

We conclude the proof as above by setting $b_0 = b_1 = 0$, $b_2 = 9(b_4 + b_5 + \cdots + b_{N-2})$ and $b_3 = -10(b_4 + b_5 + \cdots + b_{N-2})$. □

Applying similar ideas we can prove the following theorem.

Theorem 4. *Let $N \geq 4$ and let $0 < m < n$ natural numbers such that $(n, m) = 1$.*

(1) *If N is not a power of a prime, then there exists $p(x) \in S_N$ such that $(nx-m)/p(x)$;*
(2) *If N is a power of a prime p, then there exists $p(x) \in S_N$ such that $(nx - m)/p(x)$ if and only if $(p, n) = 1$.*

Proof. Let $N \geq 4$ and $p(x) = (n\,x - m)(b_0 + b_1 x + b_2 x^2 + \cdots + a_{N-2} x^{N-2})$. The condition

$$\int_0^1 p(x)\,\mathrm{d}x = \frac{1}{d_N}$$

is equivalent to

$$\sum_{k=0}^{N-2} d_N \frac{(k+1)(n-m) - m}{(k+1)(k+2)}\, b_k = 1. \tag{6}$$

If N is not a power of a prime, then we are able to prove that the coefficients of the Diophantine equation (6) are relatively prime. In order to prove the coprimality, we suppose that there exists a prime q dividing

$$d_N \frac{(k+1)(n-m) - m}{(k+1)(k+2)}$$

for every $k = 1, 2, \ldots, N-2$, with the goal of obtaining a contradiction. Let $H = q^j$, with $j = \max\{i : q^i \leq N\}$ and consider the coefficient

$$d_N \frac{(H-1)(n-m) - m}{H(H-1)} = \frac{d_N}{H}\, n - \frac{d_N}{H-1}\, m, \tag{7}$$

which arise from $k = H - 2$. By the definition of H, q does not divide d_N/H and divides $d_N/(H-1)$. If q does not divide n then q does not divide (7) and we reach the desired contradiction. If instead q divides n, and then does not divide m, therefore q does not divide the coefficient

$$d_N \frac{H(n-m) - m}{H(H+1)} = d_N \frac{n}{H+1} - \frac{d_N}{H}\, m,$$

which arise from $k = H - 1$, and this leads again to contradiction.

If N is a power of a prime, namely $N = p^k$ with $k \geq 1$, and $(n, p) > 1$ this implies that p divides all the coefficients

$$d_N \frac{(k+1)(n-m) - m}{(k+1)(k+2)}$$

and then the equation (6) has no solutions.

Finally if $N = p^k$ and $(n, p) = 1$ then we suppose that a prime q divides all the coefficients of the equation (6) and find as above that one of such coefficient is not divisible by q, a contradiction. □

4. Integer polynomials in S_N non-negative in $[0,1]$

In the first paper of the series we proposed the following conjecture:

Conjecture. *For every N, or at least for infinitely many values of N, there exists an integer polynomial $p(x) \in S_N$ such that $p(x) \geq 0$ in the interval $[0,1]$.*

A straightforward way to obtain a negative conclusion about the existence of integer polynomials of S_N non-negative in $[0,1]$ is to consider $0 \leq x_1 < x_2 < x_3 \cdots < x_n \leq 1$ and a generic polynomial $p(x) \in S_N$ in the form

$$p(x) = \sum_{k=0}^{N-1} a_k x^k.$$

Since $p(x) \in S_N$, we have

$$\int_0^1 p(x)\,\mathrm{d}x = \frac{1}{d_N},$$

that is

$$\sum_{k=0}^{N-1} \frac{d_N}{k+1} a_k = 1$$

and consider the following linear Diophantine system composed of an equality and n inequalities

$$\begin{cases} \sum_{k=0}^{N-1} \frac{d_N}{k+1} a_k = 1 \\ p(x_1) \geq 0 \\ p(x_2) \geq 0 \\ \dots \\ p(x_n) \geq 0. \end{cases} \tag{8}$$

If we are able to prove that, for a fixed value of N, the above linear system have no integer solutions $a_1, a_2 \dots a_{N-1}$, we obtain that there not exists an integer polynomial $p(x) \in S_N$ such that $p(x) \geq 0$ in the interval $[0,1]$.

By the branch and cut algorithm, used in many mathematical software systems, we can verify in deterministic way that for $N = 5$ and $x_k = k/4$, with $k = 0, 1, \dots, 4$, the system (8) has no integer solutions, although it has infinitely many real solutions, which implies that there are no integer polynomials $p(x) \in S_5$ such that $p(x) \geq 0$ in the interval $[0,1]$. Hence we disproved the strong form of the conjecture.

For $N = 6$ there exists the polynomial $p(x) = x^3(1-x)^2 \in S_6$, non-negative for all values of $x \in [0,1]$. Then the case $N = 5$ might appears as an exceptional case. Instead we can verify that for many values of N there not exists a polynomial in S_N non-negative in $[0,1]$. More precisely we can verify that there not exists an integer polynomial $p(x) \in S_N$ such that $p(x) \geq 0$ in the interval $[0,1]$ for all $7 \leq N \leq 20$, with the only exclusion of the case $N = 10$, for which we have the polynomial $p(x) = x^3(1-x)^4(2x-1)^2$.

To find out any others non-negative polynomials it might be difficult because the calculations involved, but one can prove that such polynomials cannot exist for large values of N. A Nikolskii-type inequality gives that there is a constant $C > 0$ such that

$$\max_{x\in[0,1]} |p(x)| \le CN^2 \int_0^1 |p(x)| \,\mathrm{d}x$$

for any polynomial $p(x)$ of degree $N-1$, see e.g. [16, Corollary 13.3.3]. If we suppose that there exists a sequence of non-negative polynomials $p_N(x) \in S_N$, we have

$$\frac{1}{d_N} = \int_0^1 p_N(x) \,\mathrm{d}x = \int_0^1 |p_N(x)| \,\mathrm{d}x \ge \frac{1}{CN^2} \max_{x\in[0,1]} |p_N(x)|$$

and hence

$$\lim_{N\to+\infty} \left(\max_{x\in[0,1]} |p_N(x)| \right)^{1/N} \le \lim_{N\to+\infty} d_N^{-1/N}.$$

It follows from the Prime Number Theorem that

$$\lim_{N\to+\infty} d_N^{-1/N} = e,$$

see [12, page 180]. On the other hand, Gorshkov's bound [12, page 187] gives that

$$\lim_{N\to+\infty} \left(\max_{x\in[0,1]} |p_N(x)| \right)^{1/N} \ge 0.42,$$

which is a contradiction. This implies that there are only finitely many values of N for which there exists a non-negative polynomial in S_N and then we have also disproved the weak form of the Conjecture.

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Dipartimento di Scienze Matematiche, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino — Italy

E-mail address: danilo.bazzanella@polito.it