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ON THE DIOPHANTINE EQUATION $1^k + 2^k + \ldots + x^k + R(x) = y^z$

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On the Diophantine equation $1^k + 2^k + \ldots + x^k + R(x) = y^z$ *)

by

M. VOORHOEVE, K. GYÖRY & R. TIJDEMAN **)

ABSTRACT

We prove the following theorem:
Let $R(x)$ be a fixed polynomial with rational integer coefficients. Let $b \neq 0$ and $k \geq 2$ be fixed rational integers such that $k \notin \{3,5\}$. Then the equation

$$1^k + 2^k + \ldots + x^k + R(x) = by^z$$

in integers $x,y \geq 1$ and $z > 1$ has only finitely many solutions.

KEY WORDS & PHRASES: *Diophantine equations, Bernoulli polynomials*

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*) This report will be submitted for publication elsewhere.

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1. INTRODUCTION

In J.J. SCHÄFFER [4] the equation

$$(1) \qquad 1^k + 2^k + \ldots + x^k = y^m$$

is studied. Schäffer proves that for fixed $k > 0$ and $m > 1$ the equation (1) has an infinite number of solutions in positive integers x and y only in the cases

(I) $k = 1, m = 2$; (II) $k = 3, m \in \{2,4\}$; (III) $k = 5, m = 2$.

He conjectures that all other solutions of (1) have $x = y = 1$, apart from $k = m = 2$, $x = 24$, $y = 70$. In [1], the present authors have extended Schäffer's result by proving that for fixed $r,b \in \mathbb{Z}$, $b \neq 0$ and fixed $k \geq 2$, $k \notin \{3,5\}$ the equation

$$(2) \qquad 1^k + 2^k + \ldots + x^k + r = by^z$$

has only finitely many solutions in integers $x,y \geq 1$ and $z > 1$ and all solutions can be effectively determined. In this paper we prove a further generalization.

THEOREM. *Let* $R(x)$ *be a fixed polynomial with rational integer coefficients. Let* $b \neq 0$ *and* $k \geq 2$ *be fixed rational integers such that* $k \notin \{3,5\}$. *Then the equation*

$$(3) \qquad 1^k + 2^k + \ldots + x^k + R(x) = by^z$$

in integers $x,y \geq 1$ *and* $z > 1$ *has only finitely many solutions.*

The proof of our theorem differs from our proof in [1] in quite a few respects. We combine a recent result of SCHINZEL and TIJDEMAN [5] with an older, ineffective theorem by W.J. LE VEQUE [2]. Thus, we can determine an effective upper bound for z, but not for x and y. However, we think that it is possible to prove an effective version of Le Veque's theorem. By such a theorem one could determine effective upper bounds for x and y, like in [1] for the equation (2).

In section 2 we quote the general results mentioned above; in section 3 we formulate a special lemma and prove that this lemma implies our Theorem. In section 4 we shall prove our lemma, thus completing the proof of the Theorem. In section 5 we show that our Theorem is not valid for $k \in \{1,3,5\}$ and discuss the number of solutions in integers $x,y \geq 1$ of (3) for fixed $z > 1$ and fixed $k \in \{1,3,5\}$.

2. AUXILIARY RESULTS

LEMMA 1. $1^k + 2^k + \ldots + x^k = \frac{1}{k+1}\,(B_{k+1}(x+1) - B_{k+1}(0))$,

where

$$B_q(x) = x^q - \frac{1}{2}qx^{q-1} + \frac{1}{6}\binom{q}{2}x^{q-2} - \ldots = \sum_{\ell=0}^{q}\binom{q}{\ell} B_\ell x^{q-\ell} \tag{4}$$

is the q*-th Bernoulli polynomial.*

PROOF. Well-known (see e.g. RADEMACHER [3], pp. 1-7). □

LEMMA 2. (Le Veque). *Let* $P(x) \in \mathbb{Q}[x]$,

$$P(x) = a_0x^N + a_1x^{N-1} + \ldots + a_N = a_0 \prod_{i=1}^{n} (x-\alpha_i)^{r_i},$$

with $a_0 \neq 0$ *and* $\alpha_i \neq \alpha_j$ *for* $i \neq j$. *Let* $0 \neq b \in \mathbb{Z}$, $m \in \mathbb{N}$ *and define* $s_i := m/(m,r_i)$. *Then the equation*

$$P(x) = by^m$$

has only finitely many solutions $x,y \in \mathbb{Z}$ *unless* $\{s_1,\ldots,s_n\}$ *is a permutation of one of the* n*-tuples*

i) $\{s,1,\ldots,1\}$, $s \geq 1$; ii) $\{2,2,1,\ldots,1\}$.

PROOF. This follows from LE VEQUE [2], theorem 1, giving the stated result in the case $b = 1$, $P \in \mathbb{Z}[x]$. Let d be an integer such that $dP(x) \in \mathbb{Z}[x]$. Then $b^{m-1}d^mP(x)$ is a polynomial with integer coefficients, satisfying

$$b^{m-1}d^mP(x) = (bdy)^m.$$

According to Le Veque's theorem there are only finitely many solutions x and bdy. □

LEMMA 3. (Schinzel, Tijdeman). *Let* $0 \neq b \in \mathbb{Z}$ *and let* $P(x) \in \mathbb{Q}[x]$ *be a polynomial with at least two distinct zeros. Then the equation*

$$P(x) = by^z$$

in integers $x, y > 1, z$ *implies that* $z < C$, *where* C *is an effectively computable constant depending only on* P *and* b.

PROOF. See SCHINZEL & TIJDEMAN [5]. For a generalization compare SHOREY, VAN DER POORTEN, TIJDEMAN, SCHINZEL [6], Theorem 2. □

3. A LEMMA; PROOF OF THE THEOREM

From section 2 it is clear that we have to prove that the polynomial

$$P(x) = B_q(x) - B_q + qR(x-1)$$

satisfies the conditions in Lemmas 2 and 3 with respect to the multiplicity of its zeros, unless $q \in \{2,4,6\}$. We shall formulate such a result, postponing its proof for the time being, and show that this result implies our Theorem.

LEMMA 4. *For* $q \geq 2$ *let* $B_q(x)$ *be the* q-*th Bernoulli polynomial. Let* $R^*(x) \in \mathbb{Z}[x]$ *and set*

$$P(x) = B_q(x) - B_q + qR^*(x). \tag{5}$$

Then

(i) $P(x)$ *has at least three zeros of odd multiplicity, unless* $q \in \{2,4,6\}$.

(ii) *For any odd prime* p, *at least two zeros of* $P(x)$ *have multiplicities relatively prime to* p.

Proof of the Theorem. Let $R(x-1) = R^*(x)$. We know from Lemma 4 that the polynomial

$$1^k + 2^k + \ldots + x^k + R(x) = \frac{1}{k+1}\left(B_{k+1}(x+1) - B_{k+1} + (k+1)R^*(x+1)\right)$$

has at least two distinct zeros. Hence it follows from the equation (3) by applying Lemma 3 that z is bounded. We may therefore assume that z is fixed. So we have obtained the following equation in integers x and y

$$(6) \qquad P(x) = by^m,$$

where P is given by (5) with $q = k+1$. Write $P(x) = a_0 \prod_{i=1}^{n} (x-\alpha_i)^{r_i}$, where $a_0 \neq 0$, $\alpha_i \neq \alpha_j$ if $i \neq j$. If $p|m$ for an odd prime p, then by Lemma 4 at least two zeros of P have multiplicities prime to p, so we may assume that $(r_1,p) = (r_2,p) = 1$. Setting $s_i = m/(m,r_i)$, we find that $p|s_1$ and $p|s_2$. If m is even, then by Lemma 4 at least three zeros have odd multiplicity, say r_1, r_2 and r_3 are odd. Hence s_1, s_2 and s_3 are even. Consequently, the exceptional cases in Lemma 2 cannot occur and thus (6) has only finitely many solutions for any $m > 1$. This proves the Theorem. □

4. PROOF OF LEMMA 4

By the Staudt-Clausen theorem (see RADEMACHER [3] p.10), the denominators of the Bernoulli numbers B_1, B_{2k} $(k = 1,2,\ldots)$ are even but not divisible by 4. Choose the minimal $d \in \mathbb{N}$ such that $dP(x) \in \mathbb{Z}[x]$, so

$$dP(x) = d\sum_{\ell=0}^{q-1} \binom{q}{\ell} B_\ell x^{q-\ell} + dqR^*(x) \in \mathbb{Z}[x],$$

hence $d\binom{q}{1} B_1 \in \mathbb{Z}$ and

$$\binom{q}{2k} dB_{2k} \in \mathbb{Z}, \qquad \text{for } k = 1,2,\ldots,[\tfrac{1}{2}(q-1)].$$

If d is odd, then necessarily $\binom{q}{1}$ and $\binom{q}{2k}$ must be even for $k = 1,2,\ldots,[\frac{1}{2}(q-1)]$. Write $q = 2^\lambda r$, where $\lambda \geq 1$ and r is odd. Then $\binom{q}{2^\lambda}$ is odd, giving a contradiction unless $r = 1$. So

(7) $\qquad$ d is odd $\iff$ $q = 2^\lambda$ for some $\lambda \geq 1$.

If $q \neq 2^\lambda$ for any $\lambda \geq 1$ then

(8) $\qquad d \equiv 2 \pmod 4$.

We distinguish three cases

A). Let $q \geq 3$ be odd. Then $d \equiv 2 \pmod 4$ and for $\ell = 1,2,4,\ldots,q-1$

$$d\binom{q}{\ell} B_\ell \equiv \binom{q}{\ell} \pmod 2.$$

Now

$$dP(x) \equiv x^{q-1} + \sum_{\lambda=1}^{\frac{1}{2}(q-1)} \binom{q}{2\lambda} x^{q-2\lambda} \pmod 2.$$

Hence,

$$d(P(x) + xP'(x)) \equiv x^{q-1} \pmod 2.$$

Any common factor of dP(x) and dP'(x) must therefore be congruent to a power of x (mod 2). Since $dP'(0) \equiv qdB_{q-1} \equiv 1 \pmod 2$, we find that dP(x) and dP'(x) are relatively prime (mod 2). So any common divisor of dP(x) and dP'(x) in $\mathbb{Z}[x]$ is of the shape $2S(x) + 1$. Write $dP(x) = T(x)Q(x)$, where $T(x) = \Pi_i T_i(x)^{k_i} \in \mathbb{Z}[x]$ contains the multiple factors of dP and $Q \in \mathbb{Z}[x]$ contains its simple factors. Then T(x) is of the shape $2S(x) + 1$ with $S \in \mathbb{Z}[x]$, so

$$Q(x) \equiv dP(x) \equiv x^{q-1} + \ldots \pmod 2.$$

Thus the degree of Q(x) is at least q-1, proving case A if q > 3. If q = 3, then

$$2P(x) \equiv 2x^3 + x \equiv 2x(x+1)(x-1) \pmod 3,$$

showing that P has three simple roots, which proves Lemma 4 if q is odd.

B). Suppose $q = 2^\lambda$ for some $\lambda \geq 1$, so d is odd. We first prove i) so we may assume that $\lambda \geq 3$. Now $\binom{q}{2k}$ is divisible by 4 unless $2k = \frac{1}{2}q = 2^{\lambda-1}$. Similarly, $\binom{q}{2k}$ is divisible by 8 unless 2k is divisible by $2^{\lambda-2}$. We have therefore for some odd d', writing $\nu = \frac{1}{4}q$

$$dP(x) \equiv dx^{4\nu} + 2x^{3\nu} + d'x^{2\nu} + 2x^{\nu} \pmod 4. \tag{9}$$

Write $dP(x) = T^2(x)Q(x)$, where $T(x), Q(x) \in \mathbb{Z}[x]$ and Q contains each factor of odd multiplicity of P in $\mathbb{Z}[x]$ exactly once. Assume that deg $Q(x) \leq 2$. Since

$$T^2(x)Q(x) \equiv x^{4\nu} + x^{2\nu} = x^{2\nu}(x^{2\nu}+1) \pmod 2,$$

$T^2(x)$ must be divisible by $x^{2\nu-2}$ (mod 2). So

$$T(x) = x^{\nu-1}T_1(x) + 2T_2(x),$$

$$T^2(x) = x^{2\nu-2}T_1^2(x) + 4T_3(x),$$

for certain $T_1, T_2, T_3 \in \mathbb{Z}[x]$. If q > 8, then $\nu > 2$ so the last identity is incompatible with (9) because of the term $2x^\nu$. Hence deg $Q \geq 3$, which proves (i). If q = 8, then d = 3 and

$$dP(x) \equiv 3x^8 + 2x^6 + x^4 + 2x^2 \equiv -x^2(x+1)(x-1)(x^2+1)(x^2+2) \pmod 4.$$

All these factors - except x^2 - are simple, so deg $Q \geq 6 > 3$ if q = 8, proving (i) in case B.

To prove (ii), let p be an odd prime and write $dP(x) = (T(x))^pQ(x)$, where $Q,T \in \mathbb{Z}[x]$ and all the roots of multiplicity divisible by p are incorporated in $(T(x))^p$. We have, writing $\mu = \frac{1}{2}q$,

$$dP(x) = (T(x))^p Q(x) \equiv x^\mu(x^\mu+1) \equiv x^\mu(x+1)^\mu \pmod 2.$$

Since μ is prime to p, Q has at least two different zeros, proving (ii) in case B.

C). Suppose q is even and $q \neq 2^\lambda$ for any λ. Then $d \equiv 2 \pmod 4$ and hence

$$dP(x) \equiv \sum_{k=1}^{\frac{1}{2}(q-2)} \binom{q}{2k} x^{2k} \equiv \sum_{\ell=1}^{q-1} \binom{q}{\ell} x^\ell \equiv (x+1)^q - x^q - 1 \pmod 2.$$

Write $q = 2^\lambda r$, where $r > 1$ is odd. Then

$$dP(x) \equiv (x+1)^q - x^q - 1 \equiv ((x+1)^r - x^r - 1)^{2^\lambda} \pmod 2.$$

Since $r > 1$ is odd, $(x+1)^r - x^r - 1$ has x and x + 1 as simple factors (mod 2). Thus

$$dP(x) \equiv x^{2^\lambda}(x+1)^{2^\lambda} H(x) \pmod 2,$$

where H(x) is neither divisible by x nor by x + 1 (mod 2). As in the preceding case, P(x) must have two roots of multiplicity prime to p. This proves part (ii) of the lemma.

In order to prove part (i) we may assume that $q \geq 10$, because $q = 2,4,6$ are the exceptional cases and $q = 8$ is treated in section B. Now d and q are even, so dq is divisible by 4 and, in view of (8)

$$dP(x) \equiv 2x^q - qx^{q-1} + \frac{1}{6} d\binom{q}{2} x^{q-2} + \ldots + dB_{q-2}\binom{q}{2}x^2 \pmod 4. \tag{10}$$

Write $dP(x) = T^2(x)Q(x)$, where $T,Q \in \mathbb{Z}[x]$ and Q(x) contains each factor of odd multiplicity of P exactly once. Let

$$T(x) \equiv x^{\lambda_1} + x^{\lambda_2} + \ldots + x^{\lambda_m} \pmod 2,$$

where $\lambda_1 > \lambda_2 > \ldots > \lambda_m \geq 0$. Then

$$T^2(x) \equiv x^{2\lambda_1} + x^{2\lambda_2} + \ldots + x^{2\lambda_m} + 2\sum_{\ell} p_\ell x^\ell \pmod 4,$$

where p_ℓ is the number of solutions of $\lambda_i + \lambda_j = \ell$, $\lambda_i < \lambda_j$, $i,j \in \{1,\ldots,m\}$.

Assume that $\deg Q < 3$. Let

$$Q(x) = ax^2 + bx + c.$$

If a is odd, then $T^2(x)Q(x) \equiv ax^{2\lambda_1+2} + \ldots \pmod 4$, which is incompatible with (10). If $4|a$, then $T^2(x)Q(x) \equiv bx^{2\lambda_1+1} + \ldots \pmod 4$ so $4|b$. By the definition of d, $dP(x)$ must have some odd coefficients, so c must be odd. Hence $T^2(x)Q(x) \equiv cx^{2\lambda_1} + \ldots \pmod 4$, which is again incompatible with (10). Thus $a \equiv 2 \pmod 4$ and $\lambda_1 = \frac{1}{2}(q-2)$. By comparing the coefficient of x^{q-1} in (10) and in $T^2(x)Q(x)$, we find that $b \equiv q \pmod 4$, so b is even and c must be odd. So $Q(x) \equiv 1 \pmod 2$ and

$$dP(x) \equiv T^2(x) \equiv x^{2\lambda_1} + x^{2\lambda_2} + \ldots + x^{2\lambda_m} \pmod 2.$$

Let $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_m\}$. We have by (10) that

(11) $$\lambda_i \in \Lambda \iff 2 \leq 2\lambda_i \leq q-2 \text{ and } \binom{q}{2\lambda_i} \equiv 1 \pmod 2.$$

Since $\frac{1}{2}(q-2) \in \Lambda$, we have that $\binom{q}{2}$ is odd, so $q \equiv 2 \pmod 4$, whence $b \equiv 2 \pmod 4$. Thus

$$dP(x) \equiv \sum_{\lambda_i \in \Lambda} (2x^{2\lambda_i+2} + 2x^{2\lambda_i+1} + cx^{2\lambda_i}) + 2\sum_{\ell} p_\ell x^\ell \pmod 4.$$

If $\lambda_i \in \Lambda$ and $\lambda_i < \frac{1}{2}(q-2)$, then by (10) the coefficient of $x^{2\lambda_i+1}$ in $dP(x)$ must vanish, so

(12) $$\left.\begin{array}{l} \lambda_i \in \Lambda \\ \lambda_i < \frac{1}{2}(q-2) \end{array}\right\} \Rightarrow p_{2\lambda_i+1} \text{ is odd.}$$

Observe that, by $q \geq 10$ we have $\frac{1}{2}(q-2) \geq 4$.

Now $\binom{q}{2}$ is odd, so $1 \in \Lambda$ by (11). Thus p_3 is odd by (12) and hence, by the definition of the numbers p_ℓ, $2 \in \Lambda$. So $\binom{q}{4}$ is odd, thus $q - 2 \equiv 4 \pmod 8$. Then also $\binom{q}{6}$ is odd, so $3 \in \Lambda$ by (11). Since $2 \in \Lambda$, p_5 is odd by (12). But if $\{1,2,3,4\} \in \Lambda$, then $p_5 = 2$. So $4 \notin \Lambda$ and $\binom{q}{8}$ is even by (11). Thus $q-6 \equiv 0 \pmod{16}$, so $\binom{q}{10} \equiv \binom{q}{12} \equiv \binom{q}{14} \equiv 0 \pmod 2$. Hence $5 \notin \Lambda$, $6 \notin \Lambda$ and $7 \notin \Lambda$. So $p_7 = 0$. But since $3 \in \Lambda$, p_7 is odd by (12). This gives a contradiction, so $\deg Q \geq 3$ if $q \geq 10$. The proof of Lemma 4 is thus complete.
$\square$

5. ON THE CASES k = 1,3,5

Consider the equation (3) for fixed $k \in \{1,3,5\}$ and fixed $z = m > 1$. Let $R^*(x) = R(x-1)$ and $q = k + 1$. Then (3) is equivalent to the equation

$$(13) \qquad P(x) = by^m,$$

where $P(x) = B_q(x) - B_q + qR^*(x)$, $q \in \{2,4,6\}$ and $b \neq 0$ is a fixed integer divisible by q.

If $q = 2$, then $P(x) = x^2 - x + 2R^*(x)$. $P(x)$ has two zeros of multiplicity 1, since $P(x) \equiv x(x-1) \pmod 2$. In view of Lemma 2, (13) has a finite number of integer solutions x,y unless $m = 2$. In the case $m = 2$ we can choose $R^*(x) = (x^2-x)(2S^2(x) + 2S(x))$ for any $S(x) \in \mathbb{Z}[x]$. In that case (13) becomes

$$(x^2-x)(2S(x)+1)^2 = by^2,$$

which amounts to Pell's equation, having an infinite number of solutions in integers $x,y \geq 1$ for infinitely many choices of b with $2|b$.

In the case $q = 4$ we have $P(x) = x^4 - 2x^3 + x^2 + 4R^*(x)$. Since $P(x) \equiv x^2(x-1)^2 \pmod 2$, by Lemma 2 the equation (13) has infinitely many solutions only if $m = 2$ or $m = 4$. If this is the case, there are infinitely many choices for $R^*(x)$ and b such that (13) has an infinite number of solutions. We may take $R^*(x) = x^2(x-1)^2(4S^4(x)+8S^3(x)+6S^2(x)+2S(x))$ for any

$S(x) \in \mathbb{Z}[x]$ and from (13) we get

$$x^2(x-1)^2(2S(x)+1)^4 = by^m, \quad m = 2 \text{ or } m = 4.$$

Both for $m = 2$ and for $m = 4$ this equation has an infinite number of solutions in integers $x,y \geq 1$ for infinitely many choices of b with $4|b$.

In the case $q = 6$, (13) is equivalent to

$$(14) \qquad 2P(x) = 2x^6 - 6x^5 + 5x^4 - x^2 + 12R^*(x) =$$
$$= x^2(x-1)^2(2x^2-2x-1) + 12R^*(x) = by^m,$$

where $12|b$. Since $2P(x) \equiv 2(x-1)^2x^2(x+1)^2 \pmod 3$, by Lemma 2 the equation (14) has infinitely many solutions in integers $x,y \geq 1$ only if $m = 2$. For infinitely many choices of $R^*(x)$ and b there is an infinite number of solutions x,y if $m = 2$. We may then choose
$R^*(x) = x^2(x-1)^2(2x^2-2x-1)(3S^2(x)+2S(x))$ for any $S(x) \in \mathbb{Z}[x]$ and (14) may be written in the form

$$x^2(x-1)^2(2x^2-2x-1)(6S(x)+1)^2 = by^2.$$

Consequently, (14) has an infinite number of solutions in integers $x,y \geq 1$ for infinitely many choices of b with $12|b$.

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