Values of certain binary partition functions represented by sum of three squares

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Numeration 2023

In 1798 Legendre proved that if N is a positive integer and

$$N = x^2 + y^2 + z^2$$

for some $x, y, z \in \mathbb{Z}$, then N is not of the form $4^k(8s + 7)$ for $k, s \in \mathbb{N}$. In particular, the natural density of the set of integers which can not be represented by sum of three squares is equal to $1/6$.

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This rises an interesting question whether, for a given sequence of integers $(u_n)_{n\in\mathbb{N}}$, there are infinitely many solutions of the Diophantine equation

$$u_n = x^2 + y^2 + z^2. \tag{1}$$

It is clear to characterize the solutions of (1) it is necessary to have a good understanding of the 2-adic behavior, or to be more precise the 2-adic valuation, of the terms of the sequence $(u_n)_{n\in\mathbb{N}}$.

Especially interesting is the case, when u_n has a combinatorial meaning. The equation (1) with $u_n = \binom{2n}{n}$ was investigated by Granville and Zhu. They characterized those $n \in \mathbb{N}$ such that (1) has a solution in x, y, z. The obtained characterization is equivalent with the existence of certain patterns in (unique) binary expansion of n.

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In particular, the set of integers n, for which $\binom{2n}{n}$ can be represented as a sum of three squares, has asymptotic density $7/8$ in the set of all natural number. The cited authors obtained also characterization of those n such that (1) with $u_n = n!$ has no solutions. A different approach, via automatic sequences, to this problem was presented by Deshouillers and Luca. They showed that if

$$S = \{n : \ n! \neq x^2 + y^2 + z^2\}$$

then

$$S(x) = \#\{n \leq x : \ n \in S\} = \frac{7}{8}x + O(x^{2/3}).$$

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This result was improved by Hajdu and Papp to

$$S(x) = 7/8x + O(x^{1/2}\log^2 x)$$

and recently by Burns to $S(x) = 7/8x + O(x^{1/2})$.

We follow the same line of research and consider the equation (1) with $u_n = b(n)$ being binary partition function. More precisely, let $b(n)$ counts the number of partitions of n with parts being powers of two. For example, $b(4) = 4$ because

$$4 = 2^2 = 2 + 2 = 1 + 1 + 2 = 1 + 1 + 1 + 1$$

are all possible representations of 4 as a sum of powers of two. The sequence $(b(n))_{n\in\mathbb{N}}$ was already introduced by Euler.

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Recall that the ordinary generating function of the sequence $(b(n))_{n\in\mathbb{N}}$ has the form

$$B(x) = \prod_{n=0}^{\infty} \frac{1}{1 - x^{2^n}} = \sum_{n=0}^{\infty} b(n)x^n.$$

As a consequence we see that $B(x)$ satisfies the functional equation $(1 - x)B(x) = B(x^2)$. Comparing coefficients on both sides we get that the sequence $(b(n))_{n\in\mathbb{N}}$ satisfies the recurrence: $b(0) = b(1) = 1$ and

$$b(2n) = b(2n - 1) + b(n), \quad b(2n + 1) = b(2n).$$

The corresponding series

$$T(x)=\frac{1}{B(x)}=\prod_{n=0}^{\infty}\left(1-x^{2^n}\right)=\sum_{n=0}^{\infty}t_nx^n$$

is the ordinary generating function for the famous Prouhet-Thue-Morse sequence $(t_n)_{n\in\mathbb{N}}$ (the PTM sequence for short). Recall that $t_n=(-1)^{s_2(n)}$, where $s_2(n)$ is the number of 1's in the unique expansion of n in base 2. Equivalently, we have $t_0=1$ and

$$t_{2n}=t_n,\quad t_{2n+1}=-t_n,\quad n\geq 0.$$

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Moreover, for $n\geq 2$, the 2-adic valuation of $b(n)$ is equal to

$$\nu_2(b(n))=\frac{1}{2}|t_n-2t_{n-1}+t_{n-2}|.$$

In particular, if $n\geq 2$, then $\nu_2(b(n))\in\{1,2\}$ or to be more precise,

$$b(n)\equiv 0 \pmod{4} \iff \nu_2(n)\equiv 0 \pmod{2} \textit{ or } \nu_2(n-1)\equiv 0 \pmod{2}. \quad (2)$$

For $m \in \mathbb{N}_+$ we define $b_m(n)$ as a convolution of m copies of $b(n)$. More precisely,

$$b_m(n) = \sum_{i_1+\ldots+i_m=n} b(i_1)\cdots b(i_m).$$

Note that $b_1(n) = b(n)$. The number $b_m(n)$ has also a combinatorial interpretation. Indeed, $b_m(n)$ is the number of binary partitions of n, where each part has one of m possible colors.

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For $m = 2^k - 1$ we have that $\nu_2(b_m(n)) \in \{1, 2\}$ for $n \geq 2^k$.

Theorem 1

Let $k \in \mathbb{N}_+$. For $n, i \in \mathbb{N}$ such that $i < 2^{k+2}$ we have

$$\nu_2(b_{2^k-1}(2^{k+2}n + i)) = \begin{cases} \nu_2(b(8n)) & \text{if } 0 \leq i < 2^k, \\ 1 & \text{if } 2^k \leq i < 2^{k+1}, \\ 2 & \text{if } 2^{k+1} \leq i < 3 \cdot 2^k, \\ 1 & \text{if } 3 \cdot 2^{k+1} \leq i < 2^{k+2}. \end{cases}$$

In particular, $\nu_2(b_{2^k-1}(n)) \in \{0, 1, 2\}$ and $\nu_2(b_{2^k-1}(n)) = 0$ if and only if $n < 2^k$.

Let

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From Gauss-Legendre's theorem and 2-adic properties of $b(n)$ we need to understand the behaviour of the sequence $b(n) \pmod{32}$. From the equality $b(2n+1) = b(2n)$ it is enough to consider $b(2n) \pmod{32}$. We thus put $u(n) := b(2n)$ and observe that

$$u(2n) = u(2n-1) + u(n), \quad u(2n+1) = u(2n-1) + 2u(n). \tag{3}$$

Proposition 2

For all $n > 0$ *we have*

$$\nu_2(u(n)) = \begin{cases} 1 & \text{if } \nu_2(n) \equiv 0 \pmod{2}, \\ 2 & \text{if } \nu_2(n) \equiv 1 \pmod{2}. \end{cases}$$

Proposition 2

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Lemma 3

For each $k, n \in \mathbb{N}$ *we have*

$$u(2^{2^{k+1}}(2n+1)) \equiv u(2(2n+1)) \pmod{32}.$$

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Proof: The Gupta-Rödseth theorem says that

$$b(2^{s+2}n) \equiv b(2^s n) \pmod{2^{\mu(s)}},$$

where $\mu(s) = \lfloor \frac{3s+4}{2} \rfloor$. Replacing s by $2k$ and $b(2^{s+2}n)$ by $u(2^{s+1}n)$, and noting that $\mu(2k) \geq 5$ for $k \in \mathbb{N}_+$ we get the statement of our lemma. $\square$

Theorem 4

Let

$$j(n) = \frac{u(4n+2)}{4} \mod 8,$$
$$k(n) = \frac{u(2n+1)}{2} \mod 8.$$

Then the sequences $(j(n))_{n\in\mathbb{N}}$ *and* $(k(n))_{n\in\mathbb{N}}$ *are 2-automatic. More precisely, for all* $n \in \mathbb{N}$ *we have*

$$j(2n) = 4 - 3t_n, \tag{4}$$
$$j(2n+1) = 4 + t_n, \tag{5}$$

and

$$k(2n) = 4 - 3t_n,\ k(2n+1) = 4 - t_n,$$

where t_n *is the* n *term in the PTM sequence.*

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Proof: Examine the behaviour of $u(n)$ (mod 32).

Theorem 5

For each $a \in \{1,3,5,7\}$ *let* $\mathbf{c}_a = (c_a(m))_{m\in\mathbb{N}}$ *be the increasing sequence such that*

$$\{n \in \mathbb{N} : \ j(n) = a\} = \{c_a(m) : \ m \in \mathbb{N}\}.$$

Then the sequence $\mathbf{c}_a$ *is 2-regular. More precisely, we have*

$$\begin{aligned} c_1(m) &= 4m - t_m + 1, \\ c_3(m) &= 4m + t_m + 2, \\ c_5(m) &= 4m - t_m + 2, \\ c_7(m) &= 4m + t_m + 1. \end{aligned}$$

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Corollary 6

The number $b(2n)$ *is not a sum of three squares if and only if*

$$n = 2^{2k-1}(8s + 2t_s + 3)$$

for some $k, s \in \mathbb{N}_+$.

The case $m = 3$

To get required characterization of S_3, we need to understand of the behaviour of $b_3(16n + i) \pmod{32}$ for $i = 0, 1, 2, 3, 8, 9, 10, 11$.

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Lemma 7

The following congruences holds:

$$b_3(8n + i + 4) \equiv 2(2i + 1 + 4(-1)^n)t_n \pmod{32},$$
$$b_3(32n + i) \equiv b_3(8n + i) \pmod{64},\ \ i = 0, 1, 2, 3, 4$$
$$b_3(8(2n + 1) + i) \equiv 4(3 + 3i - i^2 - 2(-1)^{n+i})t_n \pmod{32}$$
$$\equiv \begin{cases} 4(3 - 2(-1)^n)t_n \pmod{32} & \text{if } i = 0, \\ 4(5 + 2(-1)^n)t_n \pmod{32} & \text{if } i = 1, \\ 4(5 - 2(-1)^n)t_n \pmod{32} & \text{if } i = 2, \\ 4(3 + 2(-1)^n)t_n \pmod{32} & \text{if } i = 3. \end{cases}$$

In particular, for each $k \in \mathbb{N}_+$ and $i \in \{0, 1, 2, 3\}$, we have

$$b_3(2^{2k}(2n + 1) + i) \equiv 2 \pmod{4},$$
$$b_3(2^{2k+1}(2n + 1) + i) \equiv b_3(8(2n + 1) + i) \pmod{32},$$

Theorem 8

We have that $n \in S_3$ if and only if

$$n = 2^{2k+1}\left(8p + 2\left\lfloor \frac{i}{2} \right\rfloor + 3 + 2(-1)^i t_p\right) + i$$

for some $i \in \{0, 1, 2, 3\}$ and $k \in \mathbb{N}_+$, $p \in \mathbb{N}$.

Theorem 8

We have that $n \in S_3$ *if and only if*

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for some $i \in \{0,1,2,3\}$ *and* $k \in \mathbb{N}_+$, $p \in \mathbb{N}$.

Proof: From the characterization of the 2-adic valuation of $b_3(n)$ and Lemma 7 we know that if $n \in S_3$, then necessary we have $n \pmod{16} \in \{0,1,2,3,8,9,10,11\}$. Then we use case by case analysis and get the result. $\square$

The case $m = 2^k - 1, k \geq 3$

To analyze the general case we express $(b_{2^k-1}(n))_{n\in\mathbb{N}}$ as the convolution of $(b_{2^k}(n))_{n\in\mathbb{N}}$ and the PTM sequence, and use the following lemma.

Lemma 9

For all $k, n \in \mathbb{N}$ we have

$$b_{2^k}(n) \equiv \binom{2^k}{n} + 2^{k+1}\binom{2^k-2}{n-2} \pmod{2^{k+2}}.$$

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We consider two cases. If $n < 2^k$, we have $\nu_2(b_{2^k-1}(n)) = 0$. It is thus sufficient for our purposes to describe $b_{2^k-1}(n)$ modulo 8.

Proposition 10

Let $k \geq 3$ and $n < 2^k$. Then

$$b_{2^k-1}(n) \equiv t_n \cdot \begin{cases} 1 \pmod 8 & \text{if } 0 \leq n < 2^{k-2}, \\ 5 \pmod 8 & \text{if } 2^{k-2} \leq n < 2^{k-1}, \\ 7 \pmod 8 & \text{if } 2^{k-1} \leq n < 3\cdot 2^{k-2}, \\ 3 \pmod 8 & \text{if } 3\cdot 2^{k-2} \leq n < 2^k. \end{cases}$$

As an immediate corollary, we can describe $n < 2^k$ such that $b_{2^k-1}(n)$ is (not) a sum of three squares.

Corollary 11

Let $k \geq 3$ and $n < 2^k$. Then $b_{2^k-1}(n)$ is not a sum of three squares of integers if and only if one of the following cases holds:

- $0 \leq n < 2^{k-2}$ *and* $t_n = -1$;
- $2^{k-1} \leq n < 3 \cdot 2^{k-2}$ *and* $t_n = 1$.

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We move on to the case $n \geq 2^k$. This time we have $\nu_2(b_{2^k-1}(n)) \in \{1, 2\}$, and by Theorem 1 we need to consider $b_{2^k-1}(n)$ modulo 32.

Lemma 12

1. *For all $k, n \in \mathbb{N}$ such that $n \leq 2^k$ we have*

$$\nu_2\left(\binom{2^k}{n}\right) = k - \nu_2(n). \tag{6}$$

2. *For all $m, n \in \mathbb{N}$ we have*

$$\binom{2m}{2n} \equiv \binom{m}{n} \pmod{2^{\nu_2(m)+1}}. \tag{7}$$

We are now ready to describe $b_{2^k-1}(n)$ modulo 32 for $n \geq 2^k$. This time, the characterization involves two terms of the PTM sequence.

Theorem 13

Fix $k, i, j \in \mathbb{N}$ such that $k \geq 3$, $i < 8$, and $j < 2^{k-3}$. Then for all $m \geq 1$ we have

$$b_{2^k-1}(2^k m + 2^{k-3} i + j) \equiv t_j(c_i t_m + d_i t_{m-1}) \pmod{32},$$

where the coefficients c_i, d_i do not depend on k and are given in Table 1.

i	0	1	2	3	4	5	6	7
c_i	1	7	3	5	9	-1	3	5
d_i	-5	-3	1	-9	-5	-3	-7	-1

Table: *The coefficients c_i, d_i.*

Proof: Consider first the case $k \geq 4$. By Lemma 9 we have

$$b_{2^k-1}(n) = \sum_{l=0}^{n} b_{2^k}(l) t_{n-l} \equiv \sum_{l=0}^{n} \binom{2^k}{l} t_{n-l} \pmod{32}.$$

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Now, by (6), the binomial coefficients with $\nu_2(l) < k-4$ vanish modulo 32. Hence, assuming that $n \geq 2^k$, the above sum simplifies to

$$b_{2^k-1}(n) \equiv \sum_{l=0}^{16} \binom{2^k}{2^{k-4}l} t_{n-2^{k-4}l} \equiv \sum_{l=0}^{16} \binom{16}{l} t_{n-2^{k-4}l} \pmod{32},$$

where the second congruence follows from (7).

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Furthermore, we can get rid of the terms with l odd, since there is an even number of them and they are all congruent to 16 modulo 32. Therefore, we get the congruence

$$b_{2^k-1}(n) \equiv \sum_{l=0}^{8} \binom{16}{2l} t_{n-2^{k-3}l} \pmod{32}.$$

In order to simplify the right-hand side, consider b_{2^k-1} at $n = 2^k m + 2^{k-3} i + j$, where $m \geq 1$, $0 \leq i < 8$, and $0 \leq j < 2^{k-3}$.

By the recurrences defining the PTM sequence, we get

$$t_{2^k m+2^{k-3}i+j-2^{k-3}l} = t_j t_{8m+i-l} = t_j \cdot \begin{cases} t_n t_{i-l} & \text{if } l \leq i, \\ -t_{n-1} t_{l-i} & \text{if } l > i. \end{cases}$$

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Hence, the claimed formula holds with the coefficients

$$c_i = \sum_{l=0}^{i} \binom{16}{2l} t_{i-l}, \quad d_i = -\sum_{l=i+1}^{8} \binom{16}{2l} t_{l-i},$$

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Corollary 14

For each $k \geq 3$ and $n \geq 2^k$ the term $b_{2^k-1}(n)$ is not a sum of three squares of integers if and only if $t_n = t_{n-2^k} = 1$. Equivalently, n is of the form

$$n = 2^k m + l,$$

where $l, j \in \mathbb{N}$ are such that $t_m = t_l$, $\nu_2(m) \equiv 1 \pmod{2}$ and $0 \leq l < 2^k$.

Counting the solutions

For real $x \geq 0$ and $m \in \mathbb{N}_+$ let

$$S_m(x) = S_m \cap [0, x] = \#\{n \leq x : b_m(n) \text{ is not a sum of three squares}\}.$$

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Using the descriptions of the sets S_{2^k-1} obtained in the previous sections for various k it is easy to check that

$$S_{2^k-1}(x) = d_k x + O(\log x),$$

where $d_1 = d_2 = 1/12$ and $d_k = 1/6$ for $k \geq 3$.

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where $d_1 = d_2 = 1/12$ and $d_k = 1/6$ for $k \geq 3$.

In the following three results we provide more precise bounds for $S_{2^k-1}(x) - d_k x$ in the case $k = 1$, $k = 2$ and $k \geq 3$, respectively. In particular, each lower and upper bound is of the form $C_1 \log_2 x + C_2$, where the constant C_1 is optimal.

Theorem 15

For every $x \geq 1$ we have

$$-2 < S_1(x) - \frac{x}{12} < \frac{1}{2}\log_2 x.$$

In particular, the natural density of the set S_1 in $\mathbb{N}$ exists and is equal to

$$\lim_{x\to+\infty} \frac{S_1(x)}{x} = \frac{1}{12}.$$

Moreover, there exists an increasing sequence $(m_k)_{k\in\mathbb{N}} \subset \mathbb{N}$ such that

$$S_1(m_l) - \frac{m_l}{12} \sim \frac{1}{2}\log_2 m_l.$$

Proof: For $x \in \mathbb{R}$ define

$$P(x) = \#\{s \in \mathbb{N} : 8s + 2t_s + 3 \leq x\}, \quad Q(x) = \sum_{k=0} P\left(\frac{x}{4^k}\right).$$

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We have that that $Q\left(\frac{x}{2}\right) = \#\{n \leq x : b(2n) \in S\}$, hence by the relation $b(2n+1) = b(2n)$, we get

$$S(x) = Q\left(\frac{x}{4}\right) + Q\left(\frac{x-1}{4}\right).$$

For $m \in \mathbb{N}$ and $i = 0, 1, 2, 3$ we have the recurrence relations

$$Q(4m+i) = Q(m) + P(4m+i).$$

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$$Q(4m+i) = Q(m) + P(4m+i).$$

Also, for $i < 8$ we have

$$P(8m+i) = m + \begin{cases} 0 & \text{if } i = 0, \\ T_m & \text{if } i = 1, 2, 3, 4, \\ 1 & \text{if } i = 5, 6, 7. \end{cases}$$

Put

$$R(x) = Q(x) - \frac{x}{6}.$$

By induction on length $L(m)$ of binary expansion of $m \in \mathbb{N}_+$ we get

$$-\frac{2}{3} \leq R(m) \leq \frac{1}{4}\lfloor \log_2 m \rfloor - \frac{1}{6}. \qquad (8)$$

Now, define $m_0 = 0$ and $m_{l+1} = 16m_l + 36$ for $l \in \mathbb{N}$. Using the recurrence relations above and the fact that $4 \mid m_l$, we get

$$R(m_{l+1}) = R(16m_l + 36) = R(4m_l) + 1 - T_{m_l} = R(m_l) + 1 - T_{m_l}.$$

By induction one can quickly prove that $T_{m_l} = 0$ for all $l \in \mathbb{N}$, and thus we get $R(m_l) = l$ and consequently $S_1(m_l) - m_l/12 = 2(l-1)$.

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Theorem 16

For all $x \geq 1$ we have

$$\left| S_3(x) - \frac{x}{12} \right| \leq \frac{1}{6} \log_2 x + \frac{3}{2}.$$

In particular, the natural density of the set S_3 in $\mathbb{N}$ exists and is equal to

$$\lim_{x \to +\infty} \frac{S_3(x)}{x} = \frac{1}{12}.$$

Moreover, there exist increasing sequences $(m_l)_{l \in \mathbb{N}}, (n_l)_{l \in \mathbb{N}} \subset \mathbb{N}$ such that

$$S_3(m_l) - \frac{m_l}{12} \sim \frac{1}{6} \log_2 m_l,$$
$$S_3(n_l) - \frac{n_l}{12} \sim -\frac{1}{6} \log_2 n_l.$$

Theorem 17

If $k \geq 3$, then for all $x \geq 2^k$ we have

$$\left| S_{2^k-1}(x) - \frac{x}{6} + 2^{k-2} \right| \leq \frac{2^{k-2}}{3}(\log_2 x - k + 17).$$

In particular, the natural density of the set S_{2^k-1} in $\mathbb{N}$ exists and is equal to

$$\lim_{x \to +\infty} \frac{S_{2^k-1}(x)}{x} = \frac{1}{6}.$$

Moreover, there exist increasing sequences $(m_l)_{l\in\mathbb{N}}, (n_l)_{l\in\mathbb{N}} \subset \mathbb{N}$ such that

$$S_{2^k-1}(m_l) - \frac{m_l}{6} \sim \frac{2^{k-2}}{3}\log_2 m_l,$$
$$S_{2^k-1}(n_l) - \frac{n_l}{6} \sim -\frac{2^{k-2}}{3}\log_2 n_l.$$

It is natural to ask whether it is possible to obtain results concerning the representation of $b_m(n)$ as a sum of three squares for any $m \in \mathbb{N}_+$.

Problem 1

Describe the set S_m for $m \in \mathbb{N}_+$.

It is natural to ask whether it is possible to obtain results concerning the representation of $b_m(n)$ as a sum of three squares for any $m \in \mathbb{N}_+$.

Problem 1

Describe the set S_m for $m \in \mathbb{N}_+$.

The direct approach we, namely reduction modulo a power of 2, is most likely not applicable in the general case, as it seems that for all $m \neq 2^k - 1$ the valuations $\nu_2(b_m(n))$ are unbounded. In such a case one would need to compute $b_m(n) \bmod 2^{\nu_2(b_m(n))+3}$ and we do not see how this can be done without prior knowledge of $\nu_2(b_m(n))$. Therefore, we expect that obtaining an exact description of S_m for even a single value $m \neq 2^k - 1$ is hard.

We obtained precise characterization of those $n \in \mathbb{N}$ such that $b(n)$ is a sum of three squares. In particular the set of such numbers has asymptotic density equal to $11/12$. A more difficult question is whether the set

$$\mathcal{T}_1 = \{n \in \mathbb{N} : \; b(2n) = \Box + \Box\}$$

is infinite or not.

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is infinite or not.

To get a clue what can be expected, we computed the values of $b(2n)$ for $n \leq 2^{20}$ and check whether $b(2n)$ is a sum of two squares. We put

$$\mathcal{T}_1(x) = \#(\mathcal{T}_1 \cap [0, x]).$$

In the table below we present the values of $\mathcal{T}(2^n)$ for $n \leq 20$.

n	1	2	3	4	5	6	7	8	9	10
$\mathcal{T}(2^n)$	2	3	6	8	14	21	37	64	106	174

n	11	12	13	14	15	16	17	18	19	20
$\mathcal{T}(2^n)$	325	617	1089	2018	3699	6804	12551	23624	44606	84176

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Our numerical computations suggest the following

Conjecture 1

The set $\mathcal{T}$ is infinite.

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The following heuristic reasoning provides further evidence towards our conjecture. More precisely, recall that the counting function of the sums of two squares up to x is $O(x/\sqrt{\log x})$. Thus, one can say that the probability that a random positive integer n can be written as a sum of two squares of integers is $c/\sqrt{\log n}$.

Since, $\log_2 b(n) \approx \frac{1}{2}(\log_2 n)^2$ one could conjecture that the expectation that $b(n)$ is a sum of two squares is $c'/\log n$ for some $c' > 0$, provided that $b(n)$ behaves like a random integer of its size. Thus, up to x, we would have at least

$$\sum_{n \leq x} \frac{1}{\log n} = \frac{x}{\log x} + O(x/\log^2 x)$$

values of n such that $b(n)$ is a sum of two squares.

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values of n such that $b(n)$ is a sum of two squares.

Conjecture 2

There exists a positive real number c such that

$$\mathcal{T}(x) = c\frac{x}{\log x} + O(x/\log^2 x)$$

as $x \to +\infty$.

Our computations seem to confirm such an expectation. Here are the values $\mathcal{T}(2^m)\frac{m}{2^m}$ for $m = 10, \ldots, 20$.

m	10	11	12	13	14	15	16	17	18	19	20
$\mathcal{T}(2^m)\frac{m}{2^m}$	1.67	1.74	1.80	1.73	1.72	1.7	1.66	1.63	1.62	1.62	1.61

Thank you for your attention;-)