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ON SEARCHING FOR SOLUTIONS OF THE DIOPHANTINE EQUATION $x^3 + y^3 + z^3 = n$

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ABSTRACT. We propose a new search algorithm to solve the equation $x^3+y^3+z^3 = n$ for a fixed value of $n > 0$. By parametrizing $|x| = \min(|x|, |y|, |z|)$, this algorithm obtains $|y|$ and $|z|$ (if they exist) by solving a quadratic equation derived from divisors of $|x|^3 \pm n$. By using several efficient number-theoretic sieves, the new algorithm is much faster on average than previous straightforward algorithms. We performed a computer search for 51 values of n below 1000 (except $n \equiv \pm 4 \pmod 9$) for which no solution has previously been found. We found eight new integer solutions for $n = 75$, 435, 444, 501, 600, 618, 912, and 969 in the range of $|x| \le 2 \cdot 10^7$.

1. INTRODUCTION

Consider the Diophantine equation

$$x^3 + y^3 + z^3 = n, \tag{1}$$

where n is a fixed positive integer and x, y and z can be any integers with minus signs allowed [4, 12, 15]. Note that there are no solutions of equation (1) when $n \equiv \pm 4 \pmod 9$ because $a^3 \equiv 0, \pm 1 \pmod 9$ for any integer a. There is no known general criterion for excluding any other values of n, although there are still many values of n for which no solution has been found.

In finding all solutions for a *range* of values of n with $\max(|x|, |y|, |z|) \le U$, a straightforward two-dimensional algorithm [3, 8, 11] takes $O(U^2)$ steps. In [8], a computer search based on this algorithm in the range of $\max(|x|, |y|, |z|) \le 2\,097\,151$ $(= 2^{21} - 1)$, $0 < n < 1000$, was discussed. This range included the ones chosen in [3] and [11]. All 5418 solutions found were deposited into the UMT file of the American Mathematical Society. In particular, the search found solutions for 17 values of n for which no solutions had been found before: $n =$ 39, 143, 180, 231, 312, 321, 367, 439, 462, 516, 542, 556, 660, 663, 754, 777, and 870. Recently, Koyama [9] extended a computer search to the range of $\max(|x|, |y|, |z|) \le 3\,414\,387$, $0 < n < 1000$, on a CRAY-2 computer. He found other solutions for $n = 439$ as $(-869\,418, -2\,281\,057, 2\,322\,404)$ and for $n = 462$ as $(1\,612\,555, 2\,598\,019, -2\,790\,488)$ in differing ranges of [8] and [9]. Conn and Vaserstein [2] presented a search method by parametrizing another variable related to (x, y, z) for a fixed value of n. They carried out a computer search in the range of $0 < n < 100$ on a Sun 4 and a Next workstation. Although they

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missed some solutions, they found solutions for $n = 39$ and 84. In particular, a solution for $n = 84$ was found as $(-8\,241\,191,\ -41\,531\,726,\ 41\,639\,611)$ beyond the range of [9]. Heath-Brown, Lioen and te Riele [6] presented a new algorithm based on the class number of $Q(\sqrt[3]{n})$ for solving equation (1) with a fixed value of n. Their algorithm takes $O(c_0\, U\ \log\ U)$ steps to find all solutions in the range of $\max(|x|,\ |y|,\ |z|) \leq U$, where the constant c_0 depends on n. They did numerical experiments for $n = 2,\ 3,\ 20,\ 30,\ 39,$ and 42 over an extended range on a CYBER 205 vector computer [6, 13]. According to recent private communications among Vaserstein, te Riele and Koyama, it appears that the solution $(117\,367,\ 134\,476,\ -159\,380)$ for $n = 39$ was independently found by these three groups in 1991. In early 1995, Jagy [7] presented a search method by parametrizing $r = x + y + z$ for a fixed value of n. He found a solution for $n = 478$ as $(-1\,368\,722,\ -13\,434\,503, 13\,439\,237)$. With these recent results included, there are 51 values of n below 1000 (and $\not\equiv \pm 4 \bmod 9$) for which no solution has been found:

$$
n = \begin{array}{cccccccccc}
30, & 33, & 42, & 52, & 74, & 75, & 110, & 114, & 156, & 165, \\
195, & 290, & 318, & 366, & 390, & 420, & 435, & 444, & 452, & 501, \\
530, & 534, & 564, & 579, & 588, & 600, & 606, & 609, & 618, & 627, \\
633, & 732, & 735, & 758, & 767, & 786, & 789, & 795, & 830, & 834, \\
861, & 894, & 903, & 906, & 912, & 921, & 933, & 948, & 964, & 969, \\
975. & & & & & & & & &
\end{array} \tag{2}
$$

In this paper, in order to find all solutions in the range of $\min(|x|,\ |y|,\ |z|) \leq L$ for a *fixed* value of n in the above list, we propose a new search algorithm that takes $O(c\, L^2)$ steps. The constant c depends on n, and the computational complexity is much smaller than that of previous straightforward algorithms [3, 8, 11]. This improved efficiency is achieved by several number-theoretic sieves in the algorithm. We show the results of a computer search that used this algorithm.

2. Outline of new search algorithm

Without loss of generality, we may take

$$|x| \leq |y| \leq |z|.$$

The solutions are generally classified into the following three cases:

Case 0 : $x \geq 0,\ y \geq 0,\ z \geq 0,$

Case 1 : $x > 0,\ y > 0,\ z < 0,$

Case 2 : $x \leq 0,\ y < 0,\ z > 0.$

In case 0, the constraint $0 < x^3 + y^3 + z^3 < 1000$ implies $z \leq 9$. Thus, it is easy to find all solutions for case 0, even if a three-dimensional exhaustive search is done, that is to say, $x,\ y,\ z$ vary independently. In order to find all solutions for case 1 and case 2 over a *range* of values of n, a two-dimensional exhaustive search with parameters y and z was done in [3, 8, 9, 11]. In order to find all solutions for case 1 and case 2 with a *fixed* value of n, we propose a one-dimensional exhaustive search with one parameter x. In case 1, we put $X = x$, $Y = y$, $Z = -z$, and $A = X^3 - n$, where X is assumed so that $X^3 > n$. In case 2, we put $X = -x$, $Y = -y$, $Z = z$, and $A = X^3 + n$. Summarizing case 1 and case 2, we have

$$Z^3 - Y^3 = A, \tag{3}$$

where $Z > Y > 0$ and $A > 0$. Equation (3) can be rewritten as a product of two divisors

$$(Z - Y)(Z^2 + ZY + Y^2) = A. \tag{4}$$

Let $C = Z - Y$ and $D = Z^2 + ZY + Y^2$. For given values of X and n, we compute A. By factorizing A, we obtain candidates for the pair of divisors C and D such that $A = CD$. By substituting $Z = C + Y$ into $D = Z^2 + ZY + Y^2$, we get

$$Y^2 + CY + \frac{C^2 - D}{3} = 0. \tag{5}$$

Note that $(C^2 - D)/3$ is an integer. The value of Y (> 0) is obtained as one of the roots of equation (5) as

$$Y = \frac{-C + \sqrt{Q}}{2}, \quad \text{where } Q = \frac{4D - C^2}{3}. \tag{6}$$

From $Z = C + Y$, we have

$$Z = \frac{C + \sqrt{Q}}{2}. \tag{7}$$

Note that Q is a positive integer because $C^2 = Z^2 - 2ZY + Y^2 < Z^2 + ZY + Y^2 = D$ and $4D \equiv C^2 \pmod 3$. If Q is a square, then Y and Z, which are represented by equations (6) and (7), become integers because $\sqrt{Q} \equiv C \pmod 2$.

3. Properties of sieves and their effect

To execute the above procedure, several sieves based on the following properties can be applied.

3.1. **Congruence restriction between n and x.** If $a = 1, 2, -3$, then $a^3 \equiv 1 \pmod 7$. If $a = -1, -2, 3$, then $a^3 \equiv -1 \pmod 7$. Since $a^3 \equiv 0, \pm 1 \pmod 7$ for any integer a, we have $Z^3 - Y^3 \equiv 0, \pm 1, \pm 2 \pmod 7$. Recall that

$$Z^3 - Y^3 = X^3 \pm n = \begin{cases} x^3 - n & \text{for case 1,} \\ -x^3 + n & \text{for case 2.} \end{cases}$$

Therefore, if $n \equiv \pm 3 \pmod 7$, then $x^3 \not\equiv 0 \pmod 7$. If $n \equiv 2, 3 \pmod 7$, then $x^3 \not\equiv -1 \pmod 7$. If $n \equiv -2, -3 \pmod 7$, then $x^3 \not\equiv 1 \pmod 7$. Thus, for given n, the value of x is restricted as follows:

Property 1.
- *If* $n \equiv 2 \pmod 7$, *then* $x \equiv 0,\ 1,\ 2,\ -3 \pmod 7$.
- *If* $n \equiv -2 \pmod 7$, *then* $x \equiv 0,\ -1,\ -2,\ 3 \pmod 7$.
- *If* $n \equiv 3 \pmod 7$, *then* $x \equiv 1,\ 2,\ -3 \pmod 7$.
- *If* $n \equiv -3 \pmod 7$, *then* $x \equiv -1,\ -2,\ 3 \pmod 7$.

If $n \equiv \pm 2 \pmod 7$, then the passing ratio for X in this sieve is $4/7$. If $n \equiv \pm 3 \pmod 7$, then the passing ratio for X in this sieve is $3/7$. Among the 51 values of n in the list (2), there are 21 values of n satisfying $n \equiv \pm 2 \pmod 7$ and 20 values of n satisfying $n \equiv \pm 3 \pmod 7$.

Since $a^3 \equiv 0, \pm 1 \pmod 9$ for any integer a, we have $Z^3 - Y^3 \equiv 0, \pm 1, \pm 2 \pmod 9$. It is well known that if $n \equiv \pm 4 \pmod 9$, there is no solution. Note that for

$b = 0, \pm 1$, congruence $x^3 \equiv b \pmod 9$ is equivalent to congruence $x \equiv b \pmod 3$. For given n such that $n \equiv \pm 2, \pm 3 \pmod 9$, the value of x is similarly restricted as follows:

Property 2.

- *If* $n \equiv 2 \pmod 9$, *then* $x \equiv 0,\ 1 \pmod 3$.
- *If* $n \equiv -2 \pmod 9$, *then* $x \equiv 0,\ -1 \pmod 3$.
- *If* $n \equiv 3 \pmod 9$, *then* $x \equiv 1 \pmod 3$.
- *If* $n \equiv -3 \pmod 9$, *then* $x \equiv -1 \pmod 3$.

If $n \equiv \pm 2 \pmod 9$, then the passing ratio for X in this sieve is $2/3$. If $n \equiv \pm 3 \pmod 9$, then the passing ratio for X in this sieve is $1/3$. Among the 51 values of n in the list (2), there are eight values of n satisfying $n \equiv \pm 2 \pmod 9$ and 41 values of n satisfying $n \equiv \pm 3 \pmod 9$. We have proven that no other values of modulus for n except 7 and 9 have the sieve effect of excluding some values of x for a solution [14].

3.2. **Factor restriction of A based on cubic residuacity.** A prime p is a factor of A $(= X^3 \pm n)$ if and only if $X^3 \equiv \mp n \pmod p$. Thus, for given n, the factors of A are restricted as follows.

Property 3. *Let p be a prime. If n is a cubic nonresidue modulo p, then A $(= X^3 \pm n)$ does not have the factor p. When* $p \equiv 2 \pmod 3$, *all values of n are cubic residues modulo p. When* $p \equiv 1 \pmod 3$, *n is a cubic residue modulo p if and only if* $n^{\frac{p-1}{3}} \equiv 1,\ 0 \pmod p$.

In advance, for fixed n, we can easily pick primes p satisfying cubic residuacity (i.e., there is a solution X for $X^3 \equiv \pm n \pmod p$) from all primes below a certain limit. Let W_m be the set of primes satisfying $p \equiv 2 \pmod 3$ and $p \leq m$. Let $V_m(n)$ be the set of primes satisfying $p \equiv 1 \pmod 3$, $n^{\frac{p-1}{3}} \equiv 1,\ 0 \pmod p$, and $p \leq m$. Let $P_m(n)$ be the set of the union of W_m and $V_m(n)$ that includes the prime 3. Note that $|P_m(n)| = |W_m| + |V_m(n)| + 1$, where $|\cdot|$ means the cardinality of a set. For example, there are 348 513 primes below 5 000 000, giving us $|W_{5\,000\,000}| = 174\,322$. Table 1 shows $|V_m(n)|$ and $|P_m(n)|$ for several values of n and $m = 5\,000\,000$. From Table 1, we can observe that $|P_m(n)|$ is about 66.7% of the number of all primes (=348 513). Using these prechosen primes, factoring based on trial and division can be more efficiently carried out.

TABLE 1. Number of primes satisfying cubic residuacity below m $(= 5\,000\,000)$

n	30	33	42	52	74	75
$\lvert V_m(n)\rvert$	58 145	58 079	57 912	58 097	58 124	58 064
$\lvert P_m(n)\rvert$	232 468	232 402	232 235	232 420	232 447	232 387

3.3. **Factor restriction between A and C.** We obtain the following theorem about the relationship of factors of A and C. Hereafter, we denote $p^e || N$ if $p^e | N$ and $p^{e+1} \nmid N$ for integer N and prime p.

Theorem 1. *Let p be a prime with* $p \equiv 2 \pmod 3$. *If* $p^e || A$ $(e \geq 1)$, *and* $p^f || C$ $(f \geq 0)$, *then* $e = f + 2g$ *and* $f \geq g$, *where g is a nonnegative integer.*

Proof. Let $\omega = \frac{-1+\sqrt{-3}}{2}$. A prime satisfying $p \equiv 2 \pmod 3$ is a prime element in $\mathbf{Z}[\omega]$. Note that $A = Z^3 - Y^3 = (Z-Y)(Z-\omega Y)(Z-\omega^2 Y)$, where $C = Z - Y$ and $D = (Z-\omega Y)(Z-\omega^2 Y)$. Assume that $Z - \omega Y = p^a \cdot D_1$ and $Z - \omega^2 Y = p^b \cdot D_2$, where $p \nmid D_1$, $p \nmid D_2$, $a \geq 0$ and $b \geq 0$. For any integers k, Y and Z, we have

$$k|(Z-\omega Y) \iff [k|Z \text{ and } k|Y] \iff k|(Z-\omega^2 Y).$$

Putting $k = p^a$ and $k = p^b$ into the above relation, we have $a = b$, which is denoted by g. Thus, $p^{2g}||D$, which implies $e = f + 2g$. Furthermore, $p^g|(Z-Y)$, that is, $p^g|C$. Thus, $f \geq g$. □

As a result of this theorem, divisor C is restricted as:

Property 4. *Let p be a prime with $p \equiv 2 \pmod 3$. Assume that $p^e||A$, where $e \geq 1$. Then $p^h|C$ and $p^f||C$, where*

$$h = \begin{cases} \lceil \frac{e}{3} \rceil + (1 - (\lceil \frac{e}{3} \rceil \bmod 2)) & \text{if } e \text{ is odd,} \\ \lceil \frac{e}{3} \rceil + (\lceil \frac{e}{3} \rceil \bmod 2) & \text{if } e \text{ is even,} \end{cases} \tag{8}$$

$h \leq f \leq e$ and $f - h$ is even.

For example, if $e = 1, 3$, then $p|C$. If $e = 5, 7, 9$, then $p^3|C$. If $e = 2, 4, 6$, then $p^2|C$. If $e = 8, 10, 12$, then $p^4|C$. If $e = 3$, then either $f = 1$ or $f = 3$. Property 4 is effective in determining the candidates for divisor C from the combination of prime factors of A. Note that, even if a prime factor p of A with $p \equiv 1 \pmod 3$ is found, we cannot determine whether it is a factor of C or not. For the prime factor 3, we obtain the following theorem.

Theorem 2. *Assume that $3^e||A$, $3^f||C$ and $3^g||D$. Then $e = f + g$ and $f \geq \lceil \frac{g}{2} \rceil$. Moreover, if $e > 0$, then $e \geq 2$, $f \geq 1$ and $g \geq 1$.*

Proof. Let $\omega = \frac{-1+\sqrt{-3}}{2}$ and $\pi = 1 - \omega$. For $Z, Y \in \mathbf{Z}$, if $\pi^a||(Z - \omega Y)$ and $\pi^b||(Z - \omega^2 Y)$, then $a = b$, which is denoted by g. Note that for $N \in \mathbf{Z}$, if $\pi^k||N$, then k is even. Since $3 = -\omega^2\pi^2$, we have $3^k||N \iff \pi^{2k}||N$ for $N \in \mathbf{Z}$. If $\pi^{2\ell}||Y$, then $g = \min(2f, 2\ell + 1)$ because $Z - \omega Y = C + \pi Y$ and $\pi^{2f}||C$. Thus, we have $2f \geq g$ and $f \geq \lceil \frac{g}{2} \rceil$. Since $C^2 \equiv D \pmod 3$, we have $3|C \iff 3|D$. □

Note that if $3|A$, then $3^2|A$, $3|C$ and $3|D$. By means of Theorem 2, divisor C is restricted as:

Property 5. *If $3^e||A$ and $e \geq 1$, then $3^h|C$, where $h = \lceil \frac{e}{3} \rceil$.*

For example, if $e = 2, 3$, then $h = 1$. If $e = 4, 5, 6$, then $h = 2$. Note that from Property 2, if $n \equiv \pm 2, \pm 3 \pmod 9$, then $3 \nmid A$. Among the 51 values of n in the list (2), there are two values of n satisfying $n \equiv \pm 1 \pmod 9$ for which A may have a factor of 3.

3.4. **Size restriction of C.** Since $C^2 < D = A/C$, we have $C < A^{1/3}$. When $X \gg n$ such that $n < 1\,000$, $X > 100\,000$, we have $A = X^3 \pm n \approx X^3$ and a weak upper bound of C is obtained as $C < X$. Furthermore, since $Z < 2^{1/3}Y$ and $Z > 2^{1/3}X$ if $X \gg n$, a stricter upper bound of C is evaluated in a term of X as:

$$C \approx \frac{X^3}{Y^2 + YZ + Z^2} < \frac{X^3}{Z^2(1 + 2^{-1/3} + 2^{-2/3})} < \frac{X}{1 + 2^{1/3} + 2^{2/3}} \approx 0.2599X.$$

This inequality implies the following property.

Property 6. $C < 0.26X$.

The combination of Properties 4, 5 and 6 is effective in finding prime factors of A, more exactly, prime factors of C. At the beginning of trial division factoring, an upper bound of searched primes is put as $B = \lfloor 0.26X \rfloor$. After prime factors $p_k^{e_k}$ of A satisfying $p_k = 3$ or $p_k \equiv 2 \pmod 3$ are found, the upper bound of primes for trial division factoring is dynamically reduced to $B = \left\lfloor \frac{0.26X}{\prod_k p_k^{h_k}} \right\rfloor$. The final upper bound B depends on the distribution of prime factors of pseudo-random values of A.

3.5. **Congruence restriction between A and C.** If $C \not\equiv 0 \pmod 3$, then $D \equiv 1 \pmod 3$. If $C \not\equiv 0 \pmod 2$, then $D \equiv 1 \pmod 2$. Thus, the following congruences of A and C for a particular modulus hold.

Property 7. $C \equiv A \pmod 6$, *that is,* $C \equiv A \pmod 2$ *and* $C \equiv A \pmod 3$.

The relationship $C \equiv A \pmod 6$ is effective in checking the appropriateness of pairs of C and D. Furthermore, by combining Properties 4, 5, 6 and 7, a kernel divisor of C, which is denoted by H, can be computed and has a congruence relationship with A as shown in the following theorem.

Theorem 3. *Let* $p_1 = 3$. *Let* p_k $(k \geq 2)$ *be a prime satisfying* $p_k \equiv 2 \pmod 3$, $p_k < p_{k+1}$ *and* $p_k < \lfloor 0.26X \rfloor$. *Assume that* $p_k^{e_k} \| A$, $e_k \geq 0$ $(k = 1, 2, 3, \ldots)$. *Let* H *be defined as*

$$H = \prod_{k=1}^{\ell} p_k^{h_k},$$

where ℓ *is the maximum integer satisfying* $H < \lfloor 0.26X \rfloor$, *and*

$$h_k = \begin{cases} \lceil \frac{e_1}{3} \rceil & \textit{if } 3^{e_1} \| A, \\ \lceil \frac{e_k}{3} \rceil + (1 - (\lceil \frac{e_k}{3} \rceil \bmod 2)) & \textit{if } p_k^{e_k} \| A,\ k \geq 2 \textit{ and } e_k \textit{ is odd}, \\ \lceil \frac{e_k}{3} \rceil + (\lceil \frac{e_k}{3} \rceil \bmod 2) & \textit{if } p_k^{e_k} \| A,\ k \geq 2 \textit{ and } e_k \textit{ is even}. \end{cases}$$

Then, $H | C$ *and* $H \equiv A \pmod 6$.

Proof. It is clear that $H | C$ because of Properties 4 and 5. Since $H \equiv C \pmod 6$ and $C \equiv A \pmod 6$, we have $H \equiv A \pmod 6$. □

If $p_k \nmid A$ for all primes $p_k \in W_m$, $m = \lfloor 0.26X \rfloor$, then $H = 1$. In Theorem 3, H is generally defined and discussed; however, when $2 | A$, the congruence $H \equiv A \pmod 2$ always holds. When $3 | A$, the congruence $H \equiv A \pmod 3$ always holds. When the factor 3 is excluded from A and H, the following property can be used as a sieve before checking each candidate of C.

Property 8. *Let* $H = 3^h H'$, $3 \nmid H'$, $A = 3^e A'$ *and* $3 \nmid A'$. *Then* $H' \equiv A' \pmod 3$.

In this sieve, two cases such that $\{H' \equiv 1 \pmod 3$ and $A' \equiv 2 \pmod 3\}$ and $\{H' \equiv 2 \pmod 3$ and $A' \equiv 1 \pmod 3\}$ are rejected, and two other cases such that $\{H' \equiv A' \equiv 1 \pmod 3\}$ and $\{H' \equiv A' \equiv 2 \pmod 3\}$ are accepted. From an extensive computer experiment, we can observe that the passing ratio for X to satisfy $H' \equiv A' \pmod 3$ is about 50% . Note that, even if $H = 1$, the passing ratio for X to satisfy $H' \equiv A' \pmod 3$ is also about 50% .

In our search algorithm, the first trial division factoring is carried out for the prime 3 and primes $\in W_B$, then congruence $H' \equiv A' \pmod 3$ is checked. If the check is successful, then the second trial division factoring is carried out for primes $\in V_B(n)$, where B is the final upper bound of the first trial division factoring. Next, the candidates of C are computed from a combination of these factoring results.

3.6. **Congruence restriction between C and n.** The value of C is more restrictive for special values of n. We can extend the result that was analyzed for $n = 30$ in [13]. If $n \equiv 3 \pmod 9$, then $x \equiv y \equiv z \equiv 1 \pmod 3$. If $a \equiv 1 \pmod 3$, then $a^3 - 3a + 2 \equiv (a-1)^2(a+2) \equiv 0 \pmod{27}$. Thus, when $n \equiv 3 \pmod 9$, we have $n \equiv x^3 + y^3 + z^3 \equiv (3x-2) + (3y-2) + (3z-2) \equiv 3(x+y+z) - 6 \pmod{27}$, which implies $x + y + z \equiv 2 + \frac{n}{3} \pmod 9$. On the ohter hand, if $n \equiv -3 \pmod 9$, then $x \equiv y \equiv z \equiv -1 \pmod 3$. If $a \equiv -1 \pmod 3$, then $a^3 - 3a - 2 \equiv (a+1)^2(a-2) \equiv 0 \pmod{27}$. Thus, when $n \equiv -3 \pmod 9$, we have $n \equiv x^3 + y^3 + z^3 \equiv (3x+2) + (3y+2) + (3z+2) \equiv 3(x+y+z) + 6 \pmod{27}$, which implies $x + y + z \equiv -2 + \frac{n}{3} \pmod 9$. These congruences imply the following property.

Property 9. *If $n \equiv \pm 3 \pmod 9$, then*

$$C \equiv \begin{cases} X - k \pmod 9 & \textit{for case 1,} \\ X + k \pmod 9 & \textit{for case 2,} \end{cases}$$

where

$$k \equiv \begin{cases} 2 + \frac{n}{3} \pmod 9 & \textit{if } n \equiv 3 \pmod 9, \\ -2 + \frac{n}{3} \pmod 9 & \textit{if } n \equiv -3 \pmod 9. \end{cases}$$

If $n \equiv \pm 3 \pmod 9$, then this sieve modulo 9 can be used in addition to the sieve modulo 6. There are 41 values of n satisfying $n \equiv \pm 3 \pmod 9$ in the list (2). They include the case for $n = 30$, which is the smallest in the list (2) and said in [4, Probl. D5] to be the most interesting.

3.7. **Congruence restriction of C based on quadratic residuacity.** If an integer b is a quadratic nonresidue modulo p for some prime p, then b is not a square. This relationship of quadratic residuacity can be applied for choosing an appropriate value of C. An application of several primes, say $p = 5,\ 7$, seems to be practically effective. Recall $Q = (4D - C^2)/3$ is a square if there is a solution for equation (1). When $p = 5$, pairs of (A, C) modulo 5 such that $(-2,\ 1), (-1,\ 2), (1,\ -2)$ and $(2,\ -1)$ imply the quadratic nonresidue condition $Q^{\frac{p-1}{2}} = Q^2 \equiv -1 \pmod 5$. Thus, the value of C is restricted by the value of A modulo 5 as follows.

Property 10.

- *If $A \equiv 1 \pmod 5$, then $C \equiv \pm 1,\ 2 \pmod 5$.*
- *If $A \equiv -1 \pmod 5$, then $C \equiv \pm 1,\ -2 \pmod 5$.*
- *If $A \equiv 2 \pmod 5$, then $C \equiv 1,\ \pm 2 \pmod 5$.*
- *If $A \equiv -2 \pmod 5$, then $C \equiv -1, \pm 2 \pmod 5$.*

The characteristic that $A \equiv 0 \pmod 5$ implies $C \equiv 0 \pmod 5$ is common to Property 4. If $A \not\equiv 0 \pmod 5$, then the passing ratio for C in this sieve is 3/5.

A similar restriction is obtained for another prime, $p = 7$. Recall $A \not\equiv \pm 3 \pmod 7$. When $A \equiv \pm 2 \pmod 7$, the value of Q is always a quadratic residue modulo 7. Pairs of (A, C) modulo 7 such that $(-1,\ 1), (-1,\ 2), (1,\ 3), (-1,\ -3), (1,\ -2)$, and $(1,\ -1)$ imply the quadratic nonresidue condition $Q^{\frac{p-1}{2}} = Q^3 \equiv -1 \pmod 7$. Thus, the value of C is restricted by the value of A modulo 7 as follows.

Property 11.

- *If* $A \equiv 1 \pmod 7$, *then* $C \equiv 1,\ 2,\ -3 \pmod 7$.
- *If* $A \equiv -1 \pmod 7$, *then* $C \equiv -1,\ -2,\ 3 \pmod 7$.

The sieve based on Property 11 is effective except for n with $n \equiv \pm 3 \pmod 7$ because $A \equiv \pm 1 \pmod 7$ if and only if $(n, x^3) \equiv (\pm 2, \pm 1)$, $(\pm 1, 0)$, and $(0, \pm 1) \pmod 7$. If $A \equiv \pm 1 \pmod 7$, then the passing ratio for C in this sieve is $3/7$.

4. The algorithm with number-theoretic sieves

By parametrizing the positive integer X in the range of $S \le X \le L$, our search algorithm utilizing all of the above properties is as follows.

Input: n, S, L

Output: A solution (x, y, z) of $x^3 + y^3 + z^3 = n$ with $S \le \min(|x|, |y|, |z|) \le L$ or a message "nonexistence" if there is no solution.

step 1: Let W_m and $V_m(n)$ be the sets of primes satisfying

$$W_m = \{p_i \mid p_i \equiv 2 \pmod 3,\ p_i \le m\},$$

$V_m(n) = \{p_i \mid p_i \equiv 1 \pmod 3,\ n^{(p_i-1)/3} \bmod p_i = \{0, 1\},\ p_i \le m\}$.
Collect primes $p_i \in W_m$ and $p_i \in V_m(n)$, where $m = \lfloor 0.26L \rfloor$.

step 2: Put $X = S$.

step 3: Check X by the values of n mod 7 and n mod 9 by using Properties 1 and 2.
If X is not appropriate as a solution **then** go to step 11 **endif**.

step 4: Compute $A = X^3 \pm n$
(A is a representative of $A_1 = X^3 - n$ and $A_2 = X^3 + n$).

step 5: Let $B = \lfloor 0.26X \rfloor$, $H = 1$ and $F = 1$.
If $3^e \| A$ $(e \ge 1)$ **then** put $H = 3^h$, $B = \lfloor B/3^h \rfloor$, $F = 3^{e-h}$ **endif**.

step 6: Find prime factors $p_i \in W_B$ of A by a revised trial division:
Do while $p_i \le B$
  if $p_i^{e_i} \| A$ $(e_i \ge 1)$
  then if $p_i^{h_i} < B$
    then put $H = H \cdot p_i^{h_i}$, $B = \lfloor B/p_i^{h_i} \rfloor$, $F = F \cdot p_i^{e_i - h_i}$
    else go to step 11 **endif**
  endif
enddo.

step 7: Let $H' = H/3^h$ $(h \ge 0)$ and $A' = A/3^e$ $(e \ge 0)$.
If $H' \not\equiv A' \pmod 3$ **then** go to step 11 **endif**.

step 8: Find prime factors $p_i \in V_B(n)$ of A by a trial division:
Do while $p_i < B$
  if $p_i^{e_i} \| A$ $(e_i \ge 1)$ **then** put $F = F \cdot p_i^{e_i}$ **endif**
enddo.

step 9: By using the information of the factors H and F of A, choose divisor C_j as $C_j = HF_j$ satisfying Properties 6, 7, 9, 10, and 11, where F_j is the jth element among combinations of factors of F.
Compute another divisor $D_j = A/C_j$ from each C_j.

step 10: **If** $Q_j = (4D_j - C_j^2)/3$ is a square for the candidate pair $(C_j,\ D_j)$ **then** compute

$$Y = \frac{-C_j + \sqrt{Q_j}}{2}, \quad Z = \frac{C_j + \sqrt{Q_j}}{2}.$$

Output (x, y, z) transformed from (X, Y, Z) according to either case 1 or case 2 **endif**.

step 11: Put $X = X + 1$.
If $X > L$ **then** output the message "nonexistence"
else go to step 3 **endif**.

Remarks.

- Step 1 corresponds to a precomputation phase; steps 2 to 11 correspond to the main phase. Step 6 and step 8 are the most time-consuming parts of the algorithm. Since the number of primes below β is about $\lfloor \beta / \log \beta \rfloor$, step 6 and step 8 require at most $0.667 \cdot \lfloor 0.26X / \log 0.26X \rfloor$ divisions for each value of X. Thus, the order of this algorithm is $O(c\,L^2)$, but the constant term c is very small on average.
- If A has no prime factors less than $0.26X$, then $C_1 = 1$ and $D_1 = A$.
- The square root $\sqrt{Q}$ is quickly computed in floating-point arithmetic and the value is rounded to the nearest integer. By squaring this integer, the squareness of Q is checked.

Numerical Example. When $n = 501$, we found a new solution for case 2. We mention the values of the intermediate variables in the algorithm. Let $19\,895\,058 \le X \le 19\,895\,059$. When $X = 19\,895\,058$, the information of $\{n \equiv -3 \pmod 9$ and $X \equiv 0 \pmod 3\}$ shows that this value of X is not a solution for both case 1 and case 2. When $X = 19\,895\,059$, the information of $\{n \equiv -3 \pmod 7$ and $X \equiv 2 \pmod 7\}$ or $\{n \equiv -3 \pmod 9$ and $X \equiv 1 \pmod 3\}$ shows that this value of X is not a solution for case 1. This value of X may be a solution for case 2, and it follows that $A = X^3 + n = 7\,874\,730\,401\,134\,188\,690\,880$. Note that $\lfloor 0.26 \times 19\,895\,059 \rfloor = 5\,172\,715$. We apply trial division factoring of step 6 with primes p_i satisfying $p_i \equiv 2 \pmod 3$ and $p_i \le 5\,172\,715$. After knowing that A has the factor 2^6, the upper bound of primes for the trial and division is reduced to $\lfloor \frac{0.26X}{2^2} \rfloor = 1\,293\,178$. Moreover, after knowing that A has the factor 5, the upper bound is reduced to $\lfloor \frac{0.26X}{2^2 \cdot 5} \rfloor = 258\,635$. After finding that A has the factor 169 553, step 6 ends with $\lfloor \frac{0.26X}{2^2 \cdot 5 \cdot 169553} \rfloor = 1$. Thus, we have $F = 2^4$ and $H = H' = 2^2 \cdot 5 \cdot 169\,553 = 3\,391\,060$, which holds $H' \equiv A'(= A) \equiv 1 \pmod 3$. Since the reduced upper bound becomes one, we do not need the trial division factoring of step 8 with primes p_i satisfying $p_i \equiv 1 \pmod 3$ and $501^{(p_i - 1)/3} \equiv 0, 1 \pmod{p_i}$. Note that, although A has factors 181 and 6 073 below 5 172 715, they are not included into the factors of F. Thus, the candidates for divisor C satisfying the exponent restiction and $A \equiv C \equiv 4 \pmod 6$ are $\{H,\ H \cdot 2^2,\ H \cdot 2^4\}$. Among these candidates, only $3\,391\,060 (= H)$ satisfies $C < 0.26X$. For $C = 3\,391\,060$, we have $Q = (4D - C^2)/3 = 3\,092\,437\,844\,334\,864$, which is a square of $55\,609\,692$. Thus, we can compute $Y = 26\,109\,316$ and $Z = 29\,500\,376$. Finally, we obtain the solution for $n = 501$ as $(-19\,895\,059,\ -26\,109\,316,\ 29\,500\,376)$.

5. Computer search and its results

By using the search algorithm mentioned in §4, we performed a computer search for solutions of equation (1) for the 51 values of n below 1000 in the list (2). The range of the search was determined as follows. The ratio Z/X is maximal when $Z - Y = 1$ and $X \gg n$, which imply

$$X \approx (Z^2 + ZY + Y^2)^{1/3} \approx (3Z^2)^{1/3} = 3^{1/3} Z^{2/3} \approx 1.442 Z^{2/3}.$$

The ratio Z/X is minimal when $X \approx 2^{-1/3} Z \approx 0.7937Z$. As a result, the range of X is represented in terms of Z as

$$1.442 Z^{2/3} < X < 0.7937Z.$$

In [9], a search for all solutions in the range of $\max(|x|, |y|, |z|) = Z \leq 3\,414\,387$ was done. That is to say, a complete search for all solutions in the range of $X \leq \lfloor 3^{1/3} \cdot 3\,414\,387^{2/3} \rfloor = 32\,702$ and a partial search for solutions in the range of $32\,702 < X \leq \lfloor 2^{-1/3} \cdot 3\,414\,387 \rfloor = 2\,710\,000$; a search for solutions in the range of $2\,710\,000 < X$ was not done.

Our new search algorithm parametrizes a positive integer X that is in the range of $S \leq X \leq L$, where $\min(|x|, |y|, |z|) = X$. To keep a continuous and exhaustive search going, we put $S = 32702$. Taking into account our computer's power, we put $L = 2 \cdot 10^7$. The CPU-time on a DEC Alpha Server 2100 computer (4 processors, 190 MHz) was about 4 months.

We found eight new integer solutions for $n = 75$, 435, 444, 501, 600, 618, 912, and 969 as shown in Table 2. Note that the solution (x', y', z') for $n = 600$ is derived from the solution (x, y, z) for $n = 75$ because $600 = 75 \cdot 2^3$ and $(x', y', z') = (2x, 2y, 2z)$. Since our search algorithm is deterministic and exhaustive, we can also confirm that there is no solution for 43 values of n below 1000 exempting the above eight values of n in the range of $|x| \leq 2 \cdot 10^7$.

Quite recently, a referee informed us of the related work [1, 5, 10]. Bremner [1, 5] presented a search method by parametrizing $m = y + z$ and x to find solutions for a fixed value of n. It appears that he and we independently found solutions for $n = 75$ (and $n = 600$). By using Bremner's search method, Lukes [10] found a new solution for $n = 110$ as (109 938 919, 16 540 290 030, −16 540 291 649) and another solution for $n = 435$ as (−981 038 126, −509 795 654 285, 509 795 655 496). These solutions were found beyond the range of our search. As a result, there are 42 values of n below 1000 (exempting $n \equiv \pm 4 \pmod 9$) for which no solutions have been found.

Table 2. New solutions

x	y	z	n
4 381 159	435 203 083	−435 203 231	75
−2 058 260	−5 434 196	5 530 891	435
3 460 795	14 820 289	−14 882 930	444
−19 895 059	−26 109 316	29 500 376	501
8 762 318	870 406 166	−870 406 462	600
5 368 580	15 435 275	−15 648 793	618
−14 232 281	−55 648 340	55 956 937	912
1 319 606	17 395 148	−17 397 679	969

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