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THUE'S THEOREM AND THE DIOPHANTINE EQUATION $x^2 - Dy^2 = \pm N$

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ABSTRACT. A constructive version of a theorem of Thue is used to provide representations of certain integers as $x^2 - Dy^2$, where $D = 2, 3, 5, 6, 7$.

1. INTRODUCTION

The idea of using Euclid's algorithm to construct solutions of $p = x^2 + y^2$ goes back to Serret [9] and Hermite [5]. (Also see Wagon [12] and Brillhart [1].) The method easily extends to $p = x^2 + ny^2$, $n = 2, 3, 5$. (See Wilker [13] for $n = 5$.)

Cornacchia [2, pp. 61–66] generalised the method to $N = x^2 + ny^2$, $n \geq 1$ and discussed the case $n < 0$ [2, pp. 66–70]. (Also see Nitaj [8] and Hardy, Muskat and Williams [3], [4], Muskat [6], Williams [14], [15].)

It is not so well known that the Serret–Hermite method can be used to find explicit solutions of $x^2 - Dy^2 = N$ when $D > 1$ is small. Nagell [7, pp. 210–212] used a nonconstructive form of a theorem of Thue [10, p. 587] to deal with $D = 2$ and 3, while a variant of Thue's theorem was also used in Uspensky and Heaslet [11, pp. 352–368] for $D = 2, 3, 5$.

In this paper we show how to obtain explicit representations of certain integers in the form $x^2 - Dy^2$ for small $D > 1$, using a constructive version of Thue's theorem based on Euclid's algorithm. Amongst other things, if $u^2 \equiv D \pmod{N}$, $D \not\equiv 1 \pmod{N}$ is soluble and $\gcd(D, N) = 1, N$ odd, we show how to find the following representations:

$N = 8k \pm 1$	$N = x^2 - 2y^2$ $-N = x^2 - 2y^2$
$N = 12k + 1$	$N = x^2 - 3y^2$
$N = 12k - 1$	$-N = x^2 - 3y^2$
$N = 5k + 1$	$N = x^2 - 5y^2$
$N = 5k - 1$	$-N = x^2 - 5y^2$
$N = 24k + 1$ or $24k - 5$	$N = x^2 - 6y^2$
$N = 24k - 1$ or $24k + 5$	$-N = x^2 - 6y^2$
$N = 28k + 1, 28k + 9$ or $28k + 25$	$N = x^2 - 7y^2$
$N = 28k - 1, 28k - 9$ or $28k - 25$	$-N = x^2 - 7y^2$

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2. Euclid's algorithm and Thue's theorem

Euclid's algorithm. Let a and b be natural numbers, $a > b$, where b does not divide a. Let $r_0 = a$, $r_1 = b$ and for $1 \le k \le n$, $r_{k-1} = r_k q_k + r_{k+1}$, where $0 < r_{k+1} < r_k$ and $r_n = 0$. Define sequences $s_0, s_1, \ldots, s_{n+1}$ and $t_0, t_1, \ldots, t_{n+1}$ by

$$s_0 = 1, s_1 = 0, t_0 = 0, t_1 = 1, t_{k-1} = t_k q_k + t_{k+1}, s_{k-1} = s_k q_k + s_{k+1},$$

for $1 \le k \le n$. Then the following are easily proved by induction:

(i) $s_k = (-1)^k |s_k|,\ t_k = (-1)^{k+1}|t_k|$;
(ii) $0 = |s_1| < |s_2| < \cdots < |s_{n+1}|$;
(iii) $1 = |t_1| < |t_2| < \cdots < |t_{n+1}|$;
(iv) $a = |t_k| r_{k-1} + |t_{k-1}| r_k$ for $1 \le k \le n+1$;
(v) $r_k = s_k a + t_k b$ for $1 \le k \le n+1$.

Theorem 1 (Thue). *Let a and b be integers, $a > b > 1$ with $\gcd(a,b) = 1$. Then the congruence $bx \equiv y \pmod{a}$ has a solution in nonzero integers x and y satisfying $|x| < \sqrt{a}, |y| \le \sqrt{a}$.*

Proof. As $r_n = \gcd(a,b) = 1$ and $a > \sqrt{a} > 1$ and the remainders $r_0, \ldots, r_n$ in Euclid's algorithm decrease strictly to 1, there is a unique index k such that $r_{k-1} > \sqrt{a} \ge r_k$. Then the equation $a = |t_k| r_{k-1} + |t_{k-1}| r_k$ gives $a \ge |t_k| r_{k-1} > |t_k|\sqrt{a}$. Hence $|t_k| < \sqrt{a}$.

Finally, $r_k = s_k a + t_k b$, so $bt_k \equiv r_k \pmod{a}$ and we can take $x = t_k, y = r_k$. □

3. The equation $x^2 - Dy^2 = \kappa N$ with small κ

Let $N \ge 1$ be an odd integer, $D > 1$ and not a perfect square. Then a necessary condition for solvability of the equation $x^2 - Dy^2 = \kappa N$ with $\gcd(x,y) = 1$ is that the congruence $u^2 \equiv D \pmod{N}$ shall be soluble. From now on we assume this, together with $\gcd(D,N) = 1$ and $1 < u < N$. Then the Jacobi symbol $\left(\frac{D}{N}\right) = 1$. We note that if N is prime, then $\left(\frac{D}{N}\right) = 1$ also implies that $u^2 \equiv D \pmod{N}$ is soluble.

If we take $a = N$ and $b = u$ in Euclid's algorithm, the integers $r_k^2 - Dt_k^2$ decrease strictly for $k = 0, \ldots, n$, from a^2 to $1 - Dt_n^2$ and are always multiples of N. For

$$r_k^2 - Dt_k^2 \equiv t_k^2 u^2 - Dt_k^2 \equiv t_k^2(u^2 - D) \equiv 0 \pmod{N}.$$

If k is chosen so that $r_{k-1} > \sqrt{N} > r_k$, as in the proof of Thue's theorem, then as

$$N = r_{k-1}|t_k| + r_k|t_{k-1}| > r_{k-1}|t_k|, \tag{1}$$

we have $|t_k| < \sqrt{N}$ and

$$-DN < r_k^2 - Dt_k^2 < N. \tag{2}$$

Hence $r_k^2 - Dt_k^2 = -lN$, $-1 < l < D$. In fact $1 \le l < D$. Hence

$$-DN < r_k^2 - Dt_k^2 \le -N. \tag{3}$$

Also $r_k^2 + lN = Dt_k^2$ and hence $Dt_k^2 > lN$. Hence

$$|t_k| > \sqrt{\frac{lN}{D}}. \tag{4}$$

From equation (1), $N > r_{k-1}|t_k|$ and hence inequality (4) implies

$$r_{k-1} < \sqrt{\frac{DN}{l}}. \tag{5}$$

4. The equation $x^2 - 2y^2 = \pm N$

The assumption $\left(\frac{2}{N}\right) = 1$ is equivalent to $N \equiv \pm 1 \pmod 8$. Also $1 \le l < 2$, so $l = 1$ and (3) gives $r_k^2 - 2t_k^2 = -N$. Hence from equation (5) with $D = 2$, $r_{k-1} < \sqrt{2N}$ and

$$-N = r_k^2 - 2t_k^2 < r_{k-1}^2 - 2t_{k-1}^2 < r_{k-1}^2 < 2N.$$

Hence $r_{k-1}^2 - 2t_{k-1}^2 = N$.

Example. Let $N = 10000000033$, a prime of the form $8n+1$. Then $u = 87196273$ gives $k = 10$, $r_{10} = 29015, t_{10} = -73627$, $r_9 = 118239, t_9 = 44612$ and $r_{10}^2 - 2t_{10}^2 = -N$, $r_9^2 - 2t_9^2 = N$.

Remark. We can express r_{k-1} and t_{k-1} in terms of r_k and t_k. The method is useful later for delineating cases when $D = 5, 6, 7$:

Using the identities

$$(6) \qquad (r_k r_{k-1} - Dt_k t_{k-1})^2 - D(t_k r_{k-1} - t_{k-1} r_k)^2 = (r_k^2 - Dt_k^2)(r_{k-1}^2 - Dt_{k-1}^2)$$

and

$$(7) \qquad (-1)^k N = r_k t_{k-1} - r_{k-1} t_k,$$

we deduce that

$$(8) \qquad r_k r_{k-1} - Dt_k t_{k-1} = \epsilon N,$$

where $\epsilon = \pm 1$.

From equation (8), we see that $\epsilon = 1$, as $t_k t_{k-1} < 0$. Hence

$$(9) \qquad r_k r_{k-1} + DT_k T_{k-1} = N,$$

where $T_k = |t_k|$. Then solving equations (7) and (9) with $D = 2$ for r_{k-1} and T_{k-1} yields

$$r_{k-1} = -r_k + 2T_k, \quad T_{k-1} = T_k - r_k,$$

5. The equation $x^2 - 3y^2 = \pm N$

The assumption $\left(\frac{3}{N}\right) = 1$ is equivalent to $N \equiv \pm 1 \pmod{12}$. From equation (3), we have $-3N < r_k^2 - 3t_k^2 \le -N$. Hence $r_k^2 - 3t_k^2 = -2N$ or $-N$.

Case 1. Assume $N \equiv 1 \pmod{12}$. Then $r_k^2 - 3t_k^2 = -N$ would imply the contradiction $r_k^2 \equiv -1 \pmod 3$.

Hence $r_k^2 - 3t_k^2 = -2N$ and inequality (5) implies $r_{k-1} < \sqrt{\frac{3N}{2}}$. Hence

$$-2N = r_k^2 - 3t_k^2 < r_{k-1}^2 - 3t_{k-1}^2 < r_{k-1}^2 < \frac{3N}{2}.$$

Consequently $r_{k-1}^2 - 3t_{k-1}^2 = N$.

We find $2r_{k-1} = -r_k + 3T_k$ and $2T_{k-1} = -r_k + T_k$.

Case 2. Assume $N \equiv -1 \pmod{12}$. Then $r_k^2 - 3t_k^2 = -2N$ would imply the contradiction $r_k^2 \equiv 2 \pmod 3$. Hence $r_k^2 - 3t_k^2 = -N$ and inequality (5) implies $r_{k-1} < \sqrt{3N}$. Hence

$$-N = r_k^2 - 3t_k^2 < r_{k-1}^2 - 3t_{k-1}^2 < r_{k-1}^2 < 3N.$$

Consequently $r_{k-1}^2 - 3t_{k-1}^2 = N$ or $2N$. However $r_{k-1}^2 - 3t_{k-1}^2 = N$ implies the contradiction $r_{k-1}^2 \equiv -1 \pmod 3$. Hence $r_{k-1}^2 - 3t_{k-1}^2 = 2N$.

We find $r_{k-1} = -r_k + 3T_k$ and $T_{k-1} = -r_k + T_k$.

6. THE EQUATION $x^2 - 5y^2 = \pm N$

The assumption $\left(\frac{5}{N}\right) = 1$ is equivalent to $N \equiv \pm 1 \pmod 5$. Then from equation (3), we have $-5N < r_k^2 - 5t_k^2 \le -N$. Hence $r_k^2 - 5t_k^2 = -4N, -3N, -2N$ or $-N$.

We cannot have $r_k^2 - 5t_k^2 = -3N$ as then $\left(\frac{5}{3}\right) = 1$. Neither can we have $r_k^2 - 5t_k^2 = -2N$, as N is odd.

Case 1. Assume $N \equiv 1 \pmod 5$. Then $r_k^2 - 5t_k^2 = -N$ would imply the contradiction $r_k^2 \equiv -1 \pmod 5$. Hence $r_k^2 - 5t_k^2 = -4N$. Then r_k and t_k are both odd. Also inequality (5) implies $r_{k-1} < \sqrt{\frac{5N}{4}}$. Hence $-N \le r_{k-1}^2 - 5t_{k-1}^2 \le N$.

Then as in the remark above, we can show

(i) if $r_{k-1}^2 - 5t_{k-1}^2 = -N$, then

$$4r_{k-1} = -3r_k + 5T_k, \quad 4T_{k-1} = -r_k + 3T_k$$

and hence $r_k \equiv -T_k \pmod 4$;

(ii) if $r_{k-1}^2 - 5t_{k-1}^2 = N$, then

$$4r_{k-1} = -r_k + 5T_k, \quad 4T_{k-1} = -r_k + T_k$$

and hence $r_k \equiv T_k \pmod 4$.

Case 2. Assume $N \equiv -1 \pmod 5$. Then $r_k^2 - 5t_k^2 = -4N$ would imply the contradiction $r_k^2 \equiv 4 \pmod 5$. Hence $r_k^2 - 5t_k^2 = -N$. Then not both r_k and t_k are odd. Also inequality (5) implies $r_{k-1} < \sqrt{5N}$ and we deduce that $-N < r_{k-1}^2 - 5t_{k-1}^2 \le 4N$. Consequently $r_{k-1}^2 - 5t_{k-1}^2 = N$ or $4N$.

Then as in the remark above, we can show

(i) if $r_{k-1}^2 - 5t_{k-1}^2 = N$, then

$$r_{k-1} = -2r_k + 5T_k, \quad T_{k-1} = -r_k + 2T_k$$

and hence $r_{k-1} \equiv -2r_k \pmod 5$;

(ii) if $r_{k-1}^2 - 5t_{k-1}^2 = 4N$, then

$$r_{k-1} = -r_k + 5T_k, \quad T_{k-1} = -r_k + T_k$$

and hence $r_{k-1} \equiv -r_k \pmod 5$.

Here is a complete classification of the possible cases:

1. $N = 5k + 1$. Then $r_k^2 - 5t_k^2 = -4N$, while r_k and t_k are odd.
   (i) $r_k \equiv -T_k \pmod 4$. Then $r_{k-1}^2 - 5t_{k-1}^2 = -N$.
   (ii) $r_k \equiv T_k \pmod 4$. Then $r_{k-1}^2 - 5t_{k-1}^2 = N$.
2. $N = 5k - 1$. Then $r_k^2 - 5t_k^2 = -N$, while r_k and t_k are not both odd.
   (i) $r_{k-1} \equiv -2r_k \pmod 5$. Then $r_{k-1}^2 - 5t_{k-1}^2 = N$.
   (ii) $r_{k-1} \equiv -r_k \pmod 5$. Then $r_{k-1}^2 - 5t_{k-1}^2 = 4N$.

7. THE EQUATION $x^2 - 6y^2 = \pm N$

The assumption $\left(\frac{6}{N}\right) = 1$ is equivalent to $N \equiv \pm 1 \pmod{24}$ or $N \equiv \pm 5 \pmod{24}$. Then from equation (3), we have $-6N < r_k^2 - 6t_k^2 \le -N$. Hence $r_k^2 - 6t_k^2 = -5N, -4N, -3N, -2N$ or $-N$. Only $-4N$ is ruled out immediately and the other possibilities can occur.

As with the case $D = 5$, there is a complete classification of the possible cases:

1. $N = 24k - 1$ or $24k + 5$.
   (i) $r_k \equiv 0 \pmod 3$. Then $r_k^2 - 6t_k^2 = -3N$, $r_{k-1}^2 - 6t_{k-1}^2 = -N$.

(ii) $r_k \not\equiv 0 \pmod 3$. Then $r_k^2 - 6t_k^2 = -N$.
(a) $r_{k-1} \equiv 0 \pmod 2$. Then $r_{k-1}^2 - 6t_{k-1}^2 = 2N$.
(b) $r_{k-1} \equiv 1 \pmod 2$. Then $r_{k-1}^2 - 6t_{k-1}^2 = 5N$.

2. $N = 24k + 1$ or $24k - 5$:
(i) $r_k \equiv 0 \pmod 2$. Then $r_k^2 - 6t_k^2 = -2N$, $r_{k-1}^2 - 6t_{k-1}^2 = N$.
(ii) $r_k \equiv 1 \pmod 2$. Then $r_k^2 - 6t_k^2 = -5N$.
(a) $r_k \equiv T_k \pmod 5$. Then $r_{k-1}^2 - 6t_{k-1}^2 = N$.
(b) $r_k \equiv -T_k \pmod 5$. Then
$$r_{k-1}^2 - 6t_{k-1}^2 = -2N,\ r_{k-2}^2 - 6t_{k-2}^2 = N.$$

8. The equation $x^2 - 7y^2 = \pm N$

The assumption $\left(\frac{7}{N}\right) = 1$ is equivalent to $N \equiv 1, 3, 9, 19, 25, 27 \pmod{28}$. As with the case $D = 6$, there is a complete classification of the possible cases:

1. $N = 28k + 1, 28k + 9$, or $28k + 25$.
(i) $r_k \equiv T_k \pmod 2$. Then $r_k^2 - 7t_k^2 = -6N$.
(a) $r_k \equiv -T_k \pmod 6$. Then $r_{k-1}^2 - 7t_{k-1}^2 = -3N$.
(1) $r_{k-1} \equiv -T_{k-1} \pmod 3$. Then $r_{k-2}^2 - 7t_{k-2}^2 = N$.
(2) $r_{k-1} \equiv T_{k-1} \pmod 3$. Then $r_{k-2}^2 - 7t_{k-2}^2 = 2N$.
(b) $r_k \equiv T_k \pmod 6$. Then $r_{k-1}^2 - 7t_{k-1}^2 = N$.
(ii) $r_k \not\equiv T_k \pmod 2$. Then $r_k^2 - 7t_k^2 = -3N$.
(a) $r_k \equiv -T_k \pmod 3$. Then $r_{k-1}^2 - 7t_{k-1}^2 = N$.
(b) $r_k \equiv T_k \pmod 3$. Then $r_{k-1}^2 - 7t_{k-1}^2 = 2N$.

2. $N = 28k + 3, 28k + 19$, or $28k + 27$.
(i) $r_k \equiv T_k \pmod 2$. Then $r_k^2 - 7t_k^2 = -2N$.
(a) $r_{k-1} \equiv -T_{k-1} \pmod 3$. Then $r_{k-1}^2 - 7t_{k-1}^2 = -N$.
(b) $r_{k-1} \equiv T_{k-1} \pmod 3$. Then $r_{k-1}^2 - 7t_{k-1}^2 = 3N$.
(ii) $r_k \not\equiv T_k \pmod 2$. Then $r_k^2 - 7t_k^2 = -N$.
(a) $r_{k-1} \equiv -T_{k-1} \pmod 3$. Then $r_{k-1}^2 - 7t_{k-1}^2 = 3N$.
(b) $r_{k-1} \equiv T_{k-1} \pmod 3$. Then $r_{k-1}^2 - 7t_{k-1}^2 = 6N$.

In cases 1(a)(2) and 2(i), the equations $r_{k-2}^2 - 7t_{k-2}^2 = 2N$ and $r_k^2 - 7t_k^2 = -2N$ give rise to equations $x^2 - 7y^2 = N, -N$, respectively, if we write $x + y\sqrt{7} = (r_{k-2} + t_{k-2}\sqrt{7})/(3 + \sqrt{7})$ and $(r_k + t_k\sqrt{7})/(3 + \sqrt{7})$, respectively. For if $x + y\sqrt{7} = (r + t\sqrt{7})/(3 + \sqrt{7})$, where r and t are odd, then $x = \frac{3r-7t}{2}$ and $y = \frac{3t-r}{2}$ are integers and $x^2 - 7y^2 = (r^2 - 7t^2)/2$.

We note that 1(a)(2) cannot occur unless $N \equiv 0 \pmod 3$ for we have

$$r_{k-1} = \frac{-5r_k + 7T_k}{6}, \qquad T_{k-1} = \frac{-r_k + 5T_k}{6} \tag{10}$$

$$r_{k-2} = \frac{-r_{k-1} + 7T_{k-1}}{3}, \qquad T_{k-2} = \frac{-r_{k-1} + T_{k-1}}{3}. \tag{11}$$

Then (10) implies $r_{k-1} + T_{k-1} = -r_k + 2T_k \equiv -r_k - T_k \equiv 0 \pmod 3$. Also (11) implies $r_{k-1} \equiv T_{k-1} \pmod 3$. Hence 3 divides r_{k-1} and T_{k-1}, and the equation $r_{k-1}^2 - 7t_{k-1}^2 = -3N$ then implies 3 divides N.

Example. $N = 57$. The congruence $u^2 \equiv 7 \pmod{57}$ has solutions $u \equiv \pm 8, \pm 11 \pmod{57}$. Then $u = 8$ gives $k = 2, r_1 = 8, t_1 = 1, r_2 = 1, t_2 = -7$, $r_k^2 - 7t_k^2 = -6N$ and $r_{k-1}^2 - 7t_{k-1}^2 = N$, while $u = 11$ gives $k = 2, r_1 = 11, t_1 = 1, r_2 = 2, t_2 = -5$ and $r_k^2 - 7t_k^2 = -3N$ and $r_{k-1}^2 - 7t_{k-1}^2 = 2N$.

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