THE ORDER OF THE FUNDAMENTAL SOLUTION OF $X^2 - DY^2 = 1$ IN $\mathbb{Z}[\sqrt{D}]/\langle D \rangle$

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Abstract

Let D be a positive integer that is not a perfect square and $x_0 + y_0\sqrt{D}$ be the fundamental solution of Pell's equation $x^2 - Dy^2 = 1$. In this article, we study the multiplicative order of the fundamental solution in $\mathbb{Z}[\sqrt{D}]/\langle D \rangle$, which we denote by $g(D)$. Ultimately, we describe the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$ in terms of x_0 and y_0 for $\ell \geq 0$, and use this to conclude that

$$g(D^{2\ell+1}) = \begin{cases} D^{2\ell+1} & \text{if order}(x_0, D) = 1 \text{ and } D \text{ is odd,} \\ 2D^{2\ell+1} & \text{if order}(x_0, D) = 2 \text{ and } D \text{ is odd,} \\ D^{2\ell+1} & \text{if } D \text{ is even} \end{cases}$$

for sufficiently large ℓ.

1. Introduction

Consider Pell's equation

$$x^2 - Dy^2 = 1 \tag{1.1}$$

where D is a positive integer that is not a perfect square. We consider the ring

$$\mathbb{Z}[\sqrt{D}] := \left\{ x + y\sqrt{D} : x, y \in \mathbb{Z} \right\}.$$

We say that $s + t\sqrt{D} \in \mathbb{Z}[\sqrt{D}]$ or $(s,t) \in \mathbb{Z}^2$ is an integer solution (or simply solution) of Equation (1.1) if $s^2 - Dt^2 = 1$. Let $x_0 + y_0\sqrt{D}$ be the fundamental solution of Pell's Equation (1.1), i.e., $x_0 + y_0\sqrt{D}$ is the smallest positive solution of

Equation (1.1). It is well-known that all the solutions of Equation (1.1) are given by

$$\left\{\pm\left(x_0 \pm y_0\sqrt{D}\right)^{\ell} : \ell \in \mathbb{Z}\right\}.$$

Let $m \geq 2$ and Φ_m be the reduction map from $\mathbb{Z}[\sqrt{D}]$ to $\mathbb{Z}[\sqrt{D}]/\langle m\rangle$ such that

$$\Phi_m(x + y\sqrt{D}) = \overline{x} + \overline{y}\sqrt{D}$$

where $\overline{x} \equiv x \pmod{m}$ and $\overline{x} \in \{0, 1, \ldots, m-1\}$ and similarly with $\overline{y}$. Since

$$(x_0 + y_0\sqrt{D})(x_0 - y_0\sqrt{D}) = x_0^2 - Dy_0^2 = 1$$

we have $(\overline{x_0} + \overline{y_0}\sqrt{D})(\overline{x_0} - \overline{y_0}\sqrt{D}) = \overline{1}$ in $\mathbb{Z}[\sqrt{D}]/\langle m\rangle$. Hence $\Phi_m(x_0 + y_0\sqrt{D})$ is an unit in the finite ring $\mathbb{Z}[\sqrt{D}]/\langle m\rangle$. We call $g_D(m)$ the multiplicative order of $\Phi_m(x_0+y_0\sqrt{D})$ in the unit ring of $\mathbb{Z}[\sqrt{D}]/\langle m\rangle$. In this article, we are interested in studying $g_m(D)$ in the case that $m = D$ and denote $g_D(D)$ by $g(D)$. We will study and obtain an explicit formula for $g(D)$.

The authors believe there is little literature on this notion of order besides [6]. In [6], Chahal and Priddis study the order of $\Phi_m(G)$ in $\mathrm{GL}_2(\mathbb{Z}/m\mathbb{Z})$ where G is the solution set for $x^2 - Dy^2 = 1$ realized as a group of 2×2 matrices with integer entries. Their order is more general than ours. We only consider the special case that $m = D$.

The order $g_m(D)$ has some applications. In [8], we use $g_k(2A)$ to find infinitely many solutions $(s, t) \in \mathbb{N}^2$ of $x^2 - ky^2 = 1$ with $s + t \equiv 1 \pmod{2A}$ and $s + kt \equiv 1 \pmod{2A}$ where $A \in \mathbb{N}$. This step is essential in the proof of the main theorem in [8]. The order $g(D)$ is also useful in finding all solutions (x, y) of the generalized Pell equation

$$x^2 - Dy^2 = k \tag{1.2}$$

satisfying the congruence conditions

$$x \equiv a \pmod{D} \quad \text{and} \quad y \equiv b \pmod{D} \tag{1.3}$$

where $\gcd(D, k) = 1$. If $u := x_0+y_0\sqrt{D}$ is the fundamental solution of $x^2-Dy^2 = 1$, then it is well-known that every solution (x, y) of Equation (1.2) is in the form of

$$x + y\sqrt{D} = \pm(x' \pm y'\sqrt{D})(x_0 \pm y_0\sqrt{D})^{\ell},$$

for $\ell \in \mathbb{Z}$ and some solution (x', y') of Equation (1.2) satisfying

$$|x'| \leq \frac{\sqrt{|k|}(\sqrt{u}+1)}{2}, \quad |y'| \leq \frac{\sqrt{|k|}(\sqrt{u}+1)}{2\sqrt{D}}. \tag{1.4}$$

We then find all of the finitely many solutions $(x_i, y_i), 1 \leq i \leq q$, of Equation (1.2) satisfying Equation (1.3) and Equation (1.4). If no such (x_i, y_i) exist, then Equation (1.2) has no solution satisfying the congruence conditions Equation (1.3) as we show below.

Proposition 1. *Let* $x_i + y_i\sqrt{D}, 1 \le i \le q$, *be the solutions of Equation* (1.2) *satisfying Equation* (1.3) *and Equation* (1.4). *The solutions of of the generalized Pell Equation* (1.2) *satisfying Equation* (1.3) *are*

$$\pm(x_i \pm y_i\sqrt{D})(x_0 \pm y_0\sqrt{D})^{ng(D)}, n \in \mathbb{Z}, 1 \le i \le q.$$

Proof. If (x, y) is a solution of Equation (1.2), we have $\gcd(x, D) = 1$ because $\gcd(k, D) = 1$. Note that if

$$x + y\sqrt{D} = (x' + y'\sqrt{D})(s + t\sqrt{D}) = (x's + y'tD) + (y's + x't)\sqrt{D} \tag{1.5}$$

then

$$\begin{cases} x \equiv x' \pmod{D}, \\ y \equiv y' \pmod{D}, \end{cases} \quad \text{if and only if} \quad \begin{cases} s \equiv 1 \pmod{D}, \\ t \equiv 0 \pmod{D}. \end{cases}$$

Indeed, if $s \equiv 1 \pmod{D}$ and $t \equiv 0 \pmod{D}$, then from Equation (1.5), we have $x \equiv x's \equiv x' \pmod{D}$ and $y \equiv y's \equiv y' \pmod{D}$. Conversely, if $x \equiv x' \pmod{D}$ and $y \equiv y' \pmod{D}$, then from Equation (1.5) again, we have $x \equiv xs + ytD \equiv xs \pmod{D}$. Thus $s \equiv 1 \pmod{D}$ because $\gcd(x, D) = 1$. Since $y = y's + x't \equiv y + xt \pmod{D}$, we have $xt \equiv 0 \pmod{D}$ and so $t \equiv 0 \pmod{D}$. Therefore, the solutions of Equation (1.2) satisfying Equation (1.3) are precisely

$$(x_i + y_i\sqrt{D})(x_0 + y_0\sqrt{D})^{ng(D)}, n \in \mathbb{Z}.$$

□

We begin by obtaining a formula for $g(D)$. We later discuss the Ankeny-Artin-Chowla and Mordell conjectures, which consider y_0 modulo D when D is prime. Afterwards, we establish some technical lemmas which allow us to prove Theorems 5 and 6. Theorems 5 and 6 are our main results, which, together with Theorem 4, tell us how the fundamental solutions of $x^2 - D^{2\ell+1}y^2 = 1$ can be constructed from the fundamental solutions of $x^2 - Dy^2 = 1$ and furthermore that

$$g(D^{2\ell+1}) = \begin{cases} D^{2\ell+1} & \text{if } \operatorname{order}(x_0, D) = 1 \text{ and } D \text{ is odd}, \\ 2D^{2\ell+1} & \text{if } \operatorname{order}(x_0, D) = 2 \text{ and } D \text{ is odd}, \\ D^{2\ell+1} & \text{if } D \text{ is even} \end{cases}$$

for sufficiently large ℓ.

2. Formula for $g(D)$

In this section, we derive a formula for $g(D)$ in terms of the fundamental solution $x_0 + y_0\sqrt{D}$.

Theorem 1. *Suppose D is a positive integer that is not a perfect square and $x_0 + y_0\sqrt{D}$ is the fundamental solution of $x^2 - Dy^2 = 1$. Then*

$$g(D) = lcm\left(order(x_0, D), \frac{D}{\gcd(y_0, D)}\right) \tag{2.1}$$

where $order(x_0, D)$ is the multiplicative order of x_0 in $\mathbb{Z}/D\mathbb{Z}$. In particular, $order(x_0, D) = 1$ if $x_0 \equiv 1 \pmod{D}$ and $order(x_0, D) = 2$ if $x_0 \not\equiv 1 \pmod{D}$.

Proof. We first note that

$$\begin{aligned}
(x_0 + y_0\sqrt{D})^\ell &= \sum_{k=0}^{\ell} \binom{\ell}{k} x_0^{\ell-k} y_0^k D^{k/2} \\
&= \sum_{0\le 2k\le \ell} \binom{\ell}{2k} x_0^{\ell-2k} y_0^{2k} D^k + \sqrt{D} \sum_{0\le 2k+1\le \ell} \binom{\ell}{2k+1} x_0^{\ell-2k-1} y_0^{2k+1} D^k \\
&\equiv \binom{\ell}{2(0)} x_0^\ell + \sqrt{D}\binom{\ell}{2(0)+1} x_0^{\ell-1} y_0 \pmod{D} \\
&= x_0^\ell + \ell x_0^{\ell-1} y_0 \sqrt{D}.
\end{aligned}$$

So if $(x_0 + y_0\sqrt{D})^\ell = 1$ in $(\mathbb{Z}/D\mathbb{Z})[\sqrt{D}]$, then $x_0^\ell \equiv 1 \pmod{D}$ and $\ell x_0^{\ell-1} y_0 \equiv 0 \pmod{D}$. This implies that $\ell y_0 \equiv 0 \pmod{D}$ and hence $\frac{D}{\gcd(y_0,D)} \mid \ell$. So

$$\mathrm{lcm}\left(\mathrm{order}(x_0, D), \frac{D}{\gcd(y_0, D)}\right) \mid \ell.$$

Therefore,

$$g(D) = \mathrm{lcm}\left(\mathrm{order}(x_0, D), \frac{D}{\gcd(y_0, D)}\right).$$

This proves Equation (2.1). The theorem now follows immediately from the fact that $x_0^2 \equiv 1 \pmod{D}$. ☐

The usual way to find the fundamental solution $x_0 + y_0\sqrt{D}$ of $x^2 - Dy^2 = 1$ is using the continued fraction expansion of $\sqrt{D}$. We state some well-known properties of continued fractions and the fundamental solutions of $\sqrt{D}$ in next lemma.

Lemma 1. *Let D be a positive integer that is not a perfect square. Suppose the continued fraction of $\sqrt{D}$ is $[a_0, \overline{a_1, \ldots, a_\ell}]$. Then we have*

(a) $a_0 = \lfloor\sqrt{D}\rfloor$ *and* $a_\ell = 2a_0$.

(b) $a_1, \ldots, a_{\ell-1}$ *is a palindrome, i.e.,* $a_j = a_{\ell-j}$ *for* $1 \le j \le \ell - 1$.

(c) Pell's equation $x^2 - Dy^2 = 1$ has its fundamental solution $x_0 + y_0\sqrt{D}$ satisfying

$$\frac{x_0}{y_0} = \begin{cases} [a_0, a_1, \ldots, a_{\ell-1}] & \text{if } \ell \text{ is even,} \\ [a_0, a_1, \ldots, a_{2\ell-1}] & \text{if } \ell \text{ is odd.} \end{cases}$$

(d) *The negative Pell's equation* $x^2 - Dy^2 = -1$ *has a solution if and only if* ℓ *is odd; in this case, the fundamental solution* $x_1 + y_1\sqrt{D}$ *satisfies*

$$\frac{x_1}{y_1} = [a_0, a_1, \ldots, a_{\ell-1}].$$

Proof. See Theorem 5.15 of [12]. □

In view of Theorem 1, to compute $g(D)$, we need to determine if $x_0 \equiv 1 \pmod{D}$ and evaluate $\gcd(y_0, D)$. Mollin and Srinivasan shows that the values of $x_0 \pmod{D}$ are closely related to the solvability of the following three generalized Pell's equations:

$$x^2 - Dy^2 = -1, \quad x^2 - Dy^2 = 2, \quad x^2 - Dy^2 = -2. \tag{2.2}$$

We first mention a classical result of Perron.

Theorem 2 ([17])**.**

(i) *If* $D > 2$ *is a positive integer that is not a perfect square, then at most one of the equations in Equation* (2.2) *is solvable.*

(ii) *If* $D = p^\ell$ *or* $D = 2p^\ell$ *for odd prime* p *and* $\ell \geq 1$*, then one and only one equation in Equation* (2.2) *is solvable.*

Proof. Part (i) is Satz 21 of §26 in [17] and part (ii) is Satz 23 of §26 in [17]. □

For $D = 2$, all three equations of Equation (2.2) are clearly solvable.

The following result by Mollin and Srinivasan describes the relation between $x_0 \pmod{D}$ and the solvability of the equations in Equation (2.2).

Theorem 3 ([13], [14])**.** *Let* $D > 2$ *be a positive integer that is not a perfect square. Let* $x_0 + y_0\sqrt{D}$ *be the fundamental solution of Pell's equation*

$$x^2 - Dy^2 = 1. \tag{2.3}$$

Then, we have the following.

(i) *The negative Pell equation* $x^2 - Dy^2 = -1$ *is solvable if and only if* $x_0 \equiv -1 \pmod{2D}$.

(ii) *The equation*

$$x^2 - Dy^2 = 2 \tag{2.4}$$

is solvable if and only if $x_0 \equiv 1 \pmod{D}$.

(iii) *The equation* $x^2 - Dy^2 = -2$ *is solvable if and only if* $x_0 \equiv -1 \pmod{D}$ *and* $x_0 \not\equiv -1 \pmod{2D}$.

Proof. In view of Lemma 1(d), the negative Pell equation is solvable if and only if ℓ is odd. Theorem 3 follows readily from Theorem 2 (i), Theorem 4.3 of [13] and Theorem 1.1 of [14]. □

Although Theorem 3 gives a necessary and sufficient condition for $x_0 \equiv 1 \pmod{D}$, there is no simple condition on D for the solvability of Equation (2.4). The next few results give simple necessary conditions for the solvability of Equation (2.4).

Lemma 2. *Suppose $x^2 - Dy^2 = 2$ is solvable. If p is an odd prime factor of D, then $p \equiv \pm 1 \pmod{8}$. Moreover, if D is odd, then $D \equiv 7 \pmod{8}$ and if D is even, then $D = 2d$ with odd d and $D \equiv \pm 2 \pmod{8}$.*

Proof. If p is an odd prime divisor of D, then $x^2 \equiv 2 \pmod{p}$ is solvable. This implies that $p \equiv \pm 1 \pmod{8}$.

Suppose D is odd and $(x, y) \in \mathbb{N}^2$ is a solution of Equation (2.4), then either $x \equiv y \equiv 0 \pmod{2}$ or $x \equiv y \equiv 1 \pmod{2}$. If $x \equiv y \equiv 0 \pmod{2}$, then $x^2 \equiv y^2 \equiv 0 \pmod{4}$. By Equation (2.4), this implies that $4 \equiv 2 \pmod{4}$. This is impossible. Hence we must have $x \equiv y \equiv 1 \pmod{2}$. Then $x^2 \equiv y^2 \equiv 1 \pmod{8}$. Hence $D \equiv 7 \pmod{8}$.

If D is even and $(x, y) \in \mathbb{N}^2$ is a solution of Equation (2.4), we write $D = 2d$. From Equation (2.4), we deduce that x is even. Hence $x^2 \equiv 0 \pmod{4}$ and $Dy^2 \equiv 2 \pmod{4}$. This implies that $D \equiv 2 \pmod{4}$ and hence d and y are odd. Since x is even, we write $x = 2x'$. Then we have $2(x')^2 - dy^2 = 1$. Since y is odd, we have that $y^2 \equiv 1 \pmod{4}$. If x' is even, then $d \equiv -1 \pmod{4}$ and so $D \equiv -2 \pmod{8}$. If x' is odd, then $d \equiv 1 \pmod{4}$ and so $D \equiv 2 \pmod{8}$. □

Corollary 1. *If $D \equiv 0, 1 \pmod{4}$, then $x^2 - Dy^2 = 2$ is insolvable and hence $x_0 \not\equiv 1 \pmod{D}$ and $order(x_0, D) = 2$.*

Corollary 2. *Let p be an odd prime and $\ell \geq 0$. Suppose $x_0 + y_0\sqrt{p^{2\ell+1}}$ is the fundamental solution of $x^2 - p^{2\ell+1}y^2 = 1$. Then $x_0 \equiv 1 \pmod{p^{2\ell+1}}$ if and only if $p \equiv 7 \pmod{8}$.*

Proof. We have that $x_0 \equiv 1 \pmod{p^{2\ell+1}}$ if and only if $x^2 - p^{2\ell+1}y^2 = 2$ is solvable by Theorem 3. So, if $x_0 \equiv 1 \pmod{p^{2\ell+1}}$, then $p^{2\ell+1} \equiv 7 \pmod{8}$ and $p \equiv \pm 1 \pmod{8}$ by Lemma 2 with $D = p^{2\ell+1}$. Hence $p \equiv 7 \pmod{8}$. Conversely, if $p \equiv 7 \pmod{8}$, then -1 and -2 are quadratic non-residues module p. Hence both $x^2 - p^{2\ell+1}y^2 = -1$ and $x^2 - p^{2\ell+1}y^2 = -2$ are insolvable. By Theorem 2 (ii) , $x^2 - p^{2\ell+1}y^2 = 2$ is solvable and hence $x_0 \equiv 1 \pmod{p^{2\ell+1}}$. □

If the continued fraction of $\sqrt{D}$ is very simple, we can find out the fundamental solutions explicitly and compute $g(D)$. For example, if $\sqrt{D} = [m, \overline{2m}]$, then

$$g(D) = \begin{cases} 2(1 + m^2) & \text{for even } m, \\ 1 + m^2 & \text{for odd } m; \end{cases}$$

and if $\sqrt{D} = [mn, \overline{n, 2mn}], \quad m, n \in \mathbb{N}, m \geq 2$, then

$$g(D) = \operatorname{lcm}\left(2, \frac{m^2n^2+m}{\gcd(2n, m^2n^2+m)}\right).$$

The next theorem evaluates $g(2^{2\ell+1})$.

Theorem 4. *For $\ell \geq 1$, we have*

$$(3+2\sqrt{2})^{2^{\ell-1}} = x_0 + y_0\sqrt{2^{2\ell+1}}, \tag{2.5}$$

where $x_0 + y_0\sqrt{2^{2\ell+1}}$ is the fundamental solution of $x^2 - 2^{2\ell+1}y^2 = 1$ and $3+2\sqrt{2}$ is the fundamental solution of $x^2 - 2y^2 = 1$. Furthermore, we have that $g(2^{2\ell+1}) = 2^{2\ell+1}$.

Proof. We prove Equation (2.5) by induction on $\ell \geq 1$. For $\ell = 1$, we have

$$(3+2\sqrt{2})^{2^0} = 3+2\sqrt{2} = 3 + \sqrt{2^{2(1)+1}}$$

so $x_0 = 3$ and $y_0 = 1$. Thus Equation (2.5) is true for $\ell = 1$.

Suppose

$$(3+2\sqrt{2})^{2^{\ell-1}} = s + t\sqrt{2^{2\ell+1}} = s + t2^{\ell}\sqrt{2}$$

for some odd integers $s, t \in \mathbb{N}$. Then

$$(3+2\sqrt{2})^{2^{\ell}} = (s+t2^{\ell}\sqrt{2})^2 = (s^2 + 2^{2\ell+1}t^2) + st\sqrt{2^{2(\ell+1)+1}}.$$

So $x_0 = s_1^2 + 2^{2\ell+1}t^2$ and $y_0 = st$. Clearly, x_0 and y_0 are odd because s and t are odd. This proves Equation (2.5).

Clearly (x_0, y_0) in Equation (2.5) is a solution of $x^2 - 2^{2\ell+1}y^2 = 1$. If $(x_1, y_1) \in \mathbb{N}^2$ is the fundamental solution of $x^2 - 2^{2\ell+1}y^2 = 1$, then

$$x_0 + y_0\sqrt{2^{2\ell+1}} = (x_1 + y_1\sqrt{2^{2\ell+1}})^j$$

for some $j \in \mathbb{N}$. On the other hand, $(x_1, y_1 2^{\ell})$ is also a solution of $x^2 - 2y^2 = 1$. Hence

$$x_1 + y_1 2^{\ell}\sqrt{2} = (3+2\sqrt{2})^i$$

for some $i \in \mathbb{N}$. Therefore, from Equation (2.5), we have

$$(3+2\sqrt{2})^{2^{\ell-1}} = x_0 + y_0\sqrt{2^{2\ell+1}} = (x_1 + y_1\sqrt{2^{2\ell+1}})^j = (3+2\sqrt{2})^{ij}.$$

So $ij = 2^{\ell-1}$ and $i = 2^m$ for some $m \geq 0$. In view of Equation (2.5), we have

$$x_1 + y_1\sqrt{2^{2\ell+1}} = (3+2\sqrt{2})^i = (3+2\sqrt{2})^{2^m} = x_0' + y_0'\sqrt{2^{2(m+1)+1}}$$

with odd $x_0', y_0' \in \mathbb{N}$. Since both y_1 and y_0' are odd, we have that $\ell = m+1$. Therefore, $j = 1$ and we conclude that $x_0 + y_0\sqrt{2^{2\ell+1}} = x_1 + y_1\sqrt{2^{2\ell+1}}$ is the fundamental solution of $x^2 - 2^{2\ell+1}y^2 = 1$.

In view of Lemma 2, the equation $x^2 - 2^{2\ell+1}y^2 = 2$ is insolvable for $\ell \geq 1$. Hence $x_0 \not\equiv 1 \pmod{2^{2\ell+1}}$ and order $\left(x_0, 2^{2\ell+1}\right) = 1$. Therefore, we have

$$g\left(2^{2\ell+1}\right) = \operatorname{lcm}\left(1, \frac{2^{2\ell+1}}{\gcd(y_0, 2^{2\ell+1})}\right) = 2^{2\ell+1}$$

for $\ell \geq 1$. This completes the proof. □

3. Ankeny, Artin and Chowla's Conjecture and Mordell's Conjecture

In this section, we study $g(p)$ for odd primes p. In view of Theorem 1, it is important to determine if $p \mid y_0$, where $x_0 + y_0\sqrt{p}$ is the fundamental solution of $x^2 - py^2 = 1$. Based on numerical checking for the first 1000 primes p, we find that p does not divide y_0. We are led to conjecture the following.

Conjecture 1. Let p be an odd prime and $x_0 + y_0\sqrt{p}$ be the fundamental solution of $x^2 - py^2 = 1$. Then $p \nmid y_0$. Hence

$$g(p) = \begin{cases} p & \text{if } p \equiv 7 \pmod 8, \\ 2p & \text{if } p \not\equiv 7 \pmod 8. \end{cases}$$

There is a famous conjecture of Ankeny, Artin and Chowla (AAC conjecture) (Conjecture 2 below) in [3] concerning the fundamental unit of the real quadratic field $\mathbb{Q}(\sqrt{p})$ where p is a prime congruent to 1 modulo 4. Mordell also made a conjecture (Conjecture 3 below) in [16] similar in nature to the AAC conjecture for a prime p congruent to 3 modulo 4. Both conjectures are still unsolved but are widely believed to be true. The AAC conjecture was first verified for all primes not exceeding 10^{11} by Van Der Poorten et al. in [18] and then for all primes not exceeding $p < 2(10^{11})$ in [19]. In [15], Mordell proved the AAC conjecture for any regular prime p, i.e., when p does not divide the class number of the number field $\mathbb{Q}\left(e^{\frac{2\pi i}{p}}\right)$. The conjecture of Mordell has also been verified for all primes not exceeding 10^7 in [5]. Both the AAC conjecture and Mordell's conjecture are widely studied. For more discussion on these conjectures, we refer readers to [1] , [7], and [9].

Conjecture 2 ([3])**.** Let p be a prime congruent to 1 modulo 4 and $\frac{1}{2}(a + b\sqrt{p})$ be the fundamental unit for $\mathbb{Q}(\sqrt{p})$ where $a, b \in \mathbb{N}$ and $a \equiv b \pmod 2$. Then $p \nmid b$.

Conjecture 3 ([16])**.** Let p be a prime congruent to 3 modulo 4. Let $x_0 + y_0\sqrt{p}$ be the fundamental solution of $x^2 - py^2 = 1$. Then $p \nmid y_0$.

Conjecture 1 is exactly the same as Mordell's conjecture for $p \equiv 3 \pmod 4$. By using the relation between the fundamental unit for $\mathbb{Q}(\sqrt{p})$ and the fundamental solutions of $x^2 - py^2 = 1$, it can be shown that Conjecture 1 is the same as the AAC Conjecture for $p \equiv 1 \pmod 4$.

Corollary 3. *If Ankeny, Artin and Chowla's conjecture and Mordell's conjecture are true, then for any odd prime p and $\ell \geq 0$, we have*

$$g(p^{2\ell+1}) = \begin{cases} p^{2\ell+1} & \text{if } p \equiv 7 \pmod 8, \\ 2p^{2\ell+1} & \text{if } p \not\equiv 7 \pmod 8. \end{cases}$$

Proof. This follows readily from Corollary 4 and $\gcd(y_0, p^{2\ell+1}) = 1$. □

From our gathered data, we observe that for $D = 2p$ we have $\gcd(y_0, 2p) = 2$ for all odd primes p except $p = 23$. We present an analogue of the AAC and Mordell's conjecture in which p is replaced by $2p$.

Conjecture 4. Let p be an odd prime and $x_0 + y_0\sqrt{2p}$ be the fundamental solution of $x^2 - 2py^2 = 1$. Then $\gcd(y_0, 2p) = 2$ except $p = 23$. For $p = 23$, $\gcd(y_0, 2(23)) = 46$. Hence for $p \neq 23$

$$g(2p) = \begin{cases} p & \text{if order } (x_0, 2p) = 1, \\ 2p & \text{if order } (x_0, 2p) = 2. \end{cases}$$

4. The order $g(D^{2\ell+1})$.

In this section, we study the order $g(D^{2\ell+1})$. In view of Theorem 1, we need to find the relation between the fundamental solutions $x_0 + y_0\sqrt{D}$ and $x_1 + y_1\sqrt{D^{2\ell+1}}$ of $x^2 - Dy^2 = 1$ and $x^2 - D^{2\ell+1}y^2 = 1$ respectively. Since

$$1 = x_1^2 - D^{2\ell+1}y_1^2 = x_1^2 - D\left(D^\ell y_1\right)^2,$$

we have that $x_1 + y_1\sqrt{D^{2\ell+1}}$ is a power of $x_0 + \sqrt{D}y_0$. Theorem 5 below gives us the exact power of $x_0 + \sqrt{D}y_0$. The prime number 3 is special among all other prime numbers in this aspect. Although the values of $g(p)$ are still undetermined (c.f. Ankeny, Artin and Chowla's and Mordell's conjectures), Theorem 6 below gives the values of $g(D^{2\ell+1})$ for sufficiently large ℓ.

For any prime number p and $m \in \mathbb{N}$, we define the exact power of p dividing m by $n_p(m)$, that is, $p^{n_p(m)} \| m$. Here $d^n \| m$ if $d^n \mid m$ but $d^{n+1} \nmid m$.

Lemma 3. *Let D be a positive integer that is not a perfect square. Suppose (x_0, y_0) is a solution of $x^2 - Dy^2 = 1$ such that $3 \nmid y_0$ and*

$$(x_0 + y_0\sqrt{D})^3 = x_0' + y_0'\sqrt{D}$$

with $\ell_1 := n_3(y_0') \geq 1$ *and* $y_0' = 3^{\ell_1} y_0 z_0$ *for some* $z_0 \in \mathbb{N}$ *with* $3 \nmid z_0$ *and* $\gcd(z_0, D) = 1$*. Then for any* $\ell \geq 1$*, we have*

$$(x_0 + y_0\sqrt{D})^{3^\ell} = x_1 + y_1\sqrt{D}$$

with $n_3(y_1) = \ell + \ell_1 - 1$ *and* $y_1 = 3^{\ell+\ell_1-1} y_0 z_1$ *for some* $z_1 \in \mathbb{N}$ *with* $3 \nmid z_1$ *and* $\gcd(z_1, D) = 1$*.*

Proof. We prove the lemma by induction on $\ell \geq 1$. The case $\ell = 1$ is true by assumption. Suppose

$$(x_0 + y_0\sqrt{D})^{3^\ell} = x_1 + y_1\sqrt{D}$$

with $n_3(y_1) = \ell + \ell_1 - 1$ and $y_1 = 3^{\ell+\ell_1-1} y_0 z_1$ for some $z_1 \in \mathbb{N}$ with $3 \nmid z_1$ and $\gcd(z_1, D) = 1$. We see that

$$(x_0 + y_0\sqrt{D})^{3^{\ell+1}} = \left(x_1 + y_1\sqrt{D}\right)^3 = \left(x_1^3 + 3x_1y_1^2D\right) + \left(3x_1^2y_1 + y_1^3D\right)\sqrt{D}.$$

Since $x_1^2 - Dy_1^2 = 1$ and $3 \mid y_1$, we must have that $3 \nmid x_1$. We conclude that

$$n_3\left(x_1^3 + 3x_1y_1^2D\right) = 0$$

and

$$n_3\left(3x_1^2y_1 + y_1^3D\right) = n_3\left(3y_1\left(x_1^2 + \frac{y_1^2D}{3}\right)\right) = n_3(3y_1) = \ell + \ell_1.$$

Moreover,

$$\begin{aligned} 3x_1^2y_1 + y_1^3D &= y_1\left(3x_1^2 + y_1^2D\right) \\ &= 3^{\ell+\ell_1} y_0 z_1 \left(x_1^2 + 3^{2\ell+2\ell_1-3} y_0^2 z_1^2 D\right) = 3^{\ell+\ell_1} y_0 z_1' \end{aligned}$$

for some $z_1' \in \mathbb{N}$ and $3 \nmid z_1'$ and $\gcd(z_1', D) = 1$ because $\gcd(x_1, D) = 1$. This proves the lemma. ☐

Lemma 4. *Let* $D \in \mathbb{N}$ *and let* $M \in \mathbb{N}$ *be such that* $p \mid D$ *if* $p \mid M$*. Then we have*

$$DM \mid \binom{M}{2j+1} D^j$$

for any $2 \leq j \leq (M-1)/2$*.*

Proof. We first note that we can write

$$\binom{M}{2j+1} D^j = (DM)\left(\frac{(M-1)\cdots(M-2j)D^{j-1}}{(2j+1)!}\right). \tag{4.1}$$

It suffices to show that

$$n_p(DM) \leq n_p\left(\binom{M}{2j+1} D^j\right) \tag{4.2}$$

for all primes $p \mid D$. It is well-known that for any prime p and $m \in \mathbb{N}$, we have

$$\begin{aligned} n_p(m!) &= \left\lfloor \frac{m}{p} \right\rfloor + \left\lfloor \frac{m}{p^2} \right\rfloor + \cdots \leq \frac{m}{p} + \frac{m}{p^2} + \cdots \\ &= m \sum_{n=1}^{\infty} \frac{1}{p^n} = m \frac{1}{p} \frac{1}{1-\frac{1}{p}} = \frac{m}{p-1} \end{aligned} \tag{4.3}$$

where $\lfloor \xi \rfloor$ is the greatest integer $\leq \xi$.

Let p be a prime dividing D. Consider first the case that $p \geq 5$. In view of Equation (4.3), we have $n_p((2j+1)!) \leq \frac{2j+1}{p-1} \leq \frac{2j+1}{4}$ and hence $n_p((2j+1)!) \leq \left\lfloor \frac{2j+1}{4} \right\rfloor$. This implies that for all $2 \leq j \leq (M-1)/2$ and $p \geq 5$, we have

$$n_p((2j+1)!) \leq \left\lfloor \frac{2j+1}{4} \right\rfloor \leq \frac{j}{2} \leq j-1 \leq n_p(D)(j-1) = n_p(D^{j-1}).$$

In view of Equation (4.1), this shows Equation (4.2) for $p_k \geq 5$.

Now, suppose $p = 2$. Note that $5! = 2^3(15)$ and $7! = 2^4(315)$, so $n_2(5!) = 3$ and $n_2(7!) = 4$. Since $2^3 \mid (M-1)(M-2)(M-3)(M-4)$ and $2^4 \mid (M-1)(M-2)(M-3)(M-4)(M-5)(M-6)$, we use Equation (4.1) to conclude that

$$n_2(DM) \leq n_2\left(\binom{M}{2j+1} D^j\right)$$

for $j = 2, 3$. For $j \geq 4$, among $M-1, M-2, \ldots, M-2j$, there are j even numbers and at least two of them are divisible by 4 because there are more than 8 consecutive integers. Thus, $2^{j+2} \mid (M-1)\cdots(M-2j)$. Note also that, by Equation (4.3), $n_2((2j+1)!) \leq \frac{2j+1}{2-1} = 2j+1$. It then follows that

$$\begin{aligned} n_2\left((M-1)\cdots(M-2j)D^{j-1}\right) &\geq n_2(D)(j-1) + (j+2) \\ &\geq j-1+j+2 = 2j+1 \geq n_2((2j+1)!) \end{aligned}$$

and hence $n_2(DM) \leq n_2\left(\binom{M}{2j+1} D^j\right)$ for $j \geq 4$. This proves Equation (4.2) for $p = 2$.

Finally, suppose $p = 3$. Then, by Equation (4.3), $n_3((2j+1)!) \leq \frac{2j+1}{3-1} = \frac{2j+1}{2} \leq j + \frac{1}{2}$ and so $n_3((2j+1)!) \leq j$. For $j \geq 2$, among $M-1, M-2, \ldots, M-2j$, there are more than 4 consecutive integers. Thus, $3 \mid (M-1)\cdots(M-2j)$. It then follows that

$$n_3\left((M-1)\cdots(M-2j)D^{j-1}\right) \geq n_3(D)(j-1)+1 \geq (j-1)+1 = j \geq n_3((2j+1)!)$$

and hence $n_3(DM) \leq n_3\left(\binom{M}{2j+1} D^j\right)$. This proves Equation (4.2) for $p = 3$.

Therefore, we have proved Equation (4.2) for all $p \mid D$ and thus we have proved the lemma. $\square$

Lemma 5. *Let D be a positive integer that is not a perfect square and $M \in \mathbb{N}$ be such that $p \mid D$ if $p \mid M$. If $(x_0, y_0) \in \mathbb{N}^2$ is a solution of $x^2 - Dy^2 = 1$ and*

$$(x_0 + y_0\sqrt{D})^M = x_1 + y_1\sqrt{D}$$

for some $x_1, y_1 \in \mathbb{N}$, then $\gcd(x_1, D) = 1$ and $y_1 = My_0y_2$ with

$$\gcd(y_2, D) = \begin{cases} 3 & \text{if } 3 \nmid y_0, 3 \| D, \frac{D}{3} \equiv -1 \pmod 3, \text{ and } 3 \mid M, \\ 1 & \text{otherwise.} \end{cases}$$

Proof. Suppose $M \in \mathbb{N}$ such that $p \mid D$ if $p \mid M$. Then we have

$$\begin{aligned} &(x_0 + y_0\sqrt{D})^M \\ &= \sum_{j=0}^{M} \binom{M}{j} x_0^{M-j} (y_0\sqrt{D})^j \\ &= \sum_{0 \le j \le M/2} \binom{M}{2j} x_0^{M-2j} y_0^{2j} D^j + \sum_{0 \le j \le (M-1)/2} \binom{M}{2j+1} x_0^{M-2j-1} (y_0\sqrt{D})^{2j+1} \\ &= \sum_{0 \le j \le M/2} \binom{M}{2j} x_0^{M-2j} y_0^{2j} D^j + \sqrt{D} \sum_{0 \le j \le (M-1)/2} \binom{M}{2j+1} x_0^{M-2j-1} y_0^{2j+1} D^j \\ &:= x_1 + y_1\sqrt{D}. \end{aligned}$$

It is known that (x_1, y_1) is also a solution of $x^2 - Dy^2 = 1$. Thus, $\gcd(x_1, D) = 1$. We now consider y_1. In view of Lemma 4, we can write

$$\sum_{2 \le j \le (M-1)/2} \binom{M}{2j+1} x_0^{M-2j-1} y_0^{2j+1} D^j = DMy_0z$$

for some $z \in \mathbb{N}$. Hence we have

$$\begin{aligned} y_1 &= \sum_{0 \le j \le (M-1)/2} \binom{M}{2j+1} x_0^{M-2j-1} y_0^{2j+1} D^j \\ &= Mx_0^{M-1}y_0 + \binom{M}{3} x_0^{M-3} y_0^3 D + DMy_0z \\ &= My_0 \left(x_0^{M-1} + \frac{(M-1)(M-2)}{6} y_0^2 D x_0^{M-3} + Dz \right) = My_0y_2 \end{aligned}$$

where

$$y_2 := x_0^{M-1} + \frac{(M-1)(M-2)}{6} y_0^2 D x_0^{M-3} + Dz.$$

It remains to evaluate

$$\gcd(y_2, D) = \gcd\left(x_0^{M-1} + \frac{(M-1)(M-2)}{6} y_0^2 D x_0^{M-3}, D \right). \tag{4.4}$$

If $3 \nmid D$, then $3 \nmid M$ and $6 \mid (M-1)(M-2)$. Hence from Equation (4.4), we have $\gcd(y_2, D) = \gcd(x_0^{M-1}, D) = 1$.

We now suppose $3 \mid D$.

If $3 \mid y_0$, then $6 \mid (M-1)(M-2)y_0^2$. Hence from Equation (4.4), we have $\gcd(y_2, D) = \gcd(x_0^{M-1}, D) = 1$.

If $3 \nmid y_0$, then

$$\begin{aligned} \gcd(y_2, D) &= \gcd\left(x_0^{M-1} + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right) x_0^{M-3}, D\right) \\ &= \gcd\left(1 + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right), D\right) \end{aligned}$$

because $\gcd(x_0, D) = 1$ and $x_0^2 - Dy_0^2 = 1$. Let p be a prime such that $p \mid D$ and $p \neq 3$. Then, $p \mid \frac{D}{3}$ and so

$$p \nmid 1 + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right).$$

Hence the only possible prime divisor of $\gcd\left(1 + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right), D\right)$ is 3.

If $3^2 \mid D$, then $3 \mid \frac{D}{3}$ and hence $3 \nmid 1 + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right)$. It follows that

$$\gcd(y_2, D) = \gcd\left(1 + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right), D\right) = 1.$$

If $3 \| D$, then $\gcd\left(1 + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right), D\right) = 1$ or 3. Also we have

$$\gcd\left(1 + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right), D\right) = 3$$

if and only if

$$1 + \frac{(M-1)(M-2)}{2} y_0^2 \left(\frac{D}{3}\right) \equiv 0 \pmod{3}$$

if and only if

$$\frac{(M-1)(M-2)}{2} \left(\frac{D}{3}\right) \equiv 2 \pmod{3}$$

because $3 \nmid y_0$ and hence $y_0^2 \equiv 1 \pmod{3}$. Since $3 \nmid \frac{D}{3}$, we have that $\frac{D}{3} \equiv \pm 1 \pmod{3}$.

If $\frac{D}{3} \equiv 1 \pmod{3}$, then

$$\frac{(M-1)(M-2)}{2} \left(\frac{D}{3}\right) \equiv 2 \pmod{3}$$

if and only if $(M-1)(M-2) \equiv 1 \pmod{3}$. However, $(M-1)(M-2) \not\equiv 1 \pmod{3}$ for any $M \in \mathbb{Z}$. So if $\frac{D}{3} \equiv 1 \pmod{3}$, then $\gcd(y_2, D) = 1$ by Equation (4.3).

If $\frac{D}{3} \equiv -1 \pmod 3$, then $\gcd\left(1+\frac{(M-1)(M-2)}{2}y_0^2\left(\frac{D}{3}\right), D\right) = 3$ if and only if $\frac{(M-1)(M-2)}{2} \equiv 1 \pmod 3$ if and only if $3 \mid M$. We conclude that

$$\gcd(y_2, D) = \begin{cases} 3 & \text{if } 3 \nmid y_0, 3 \| D, \frac{D}{3} \equiv -1 \pmod 3, \text{ and } 3 \mid M, \\ 1 & \text{otherwise.} \end{cases}$$

□

Theorem 5. *Let D be a positive integer that is not a perfect square and let $x_0 + y_0\sqrt{D}$ be the fundamental solution of $x^2 - Dy^2 = 1$. Suppose $D^{\ell_0} \| y_0$ for some $\ell_0 \geq 0$ and $\ell_1 := n_3\left(3x_0^2y_0 + Dy_0^3\right)$. We have three cases:*

(i) In the case that $0 \leq \ell \leq \ell_0$, we have that $(x_0, y_0D^{-\ell})$ is the fundamental solution of $x^2 - D^{2\ell+1}y = 1$.

(ii) In the case that $\ell_0 < \ell$ and

$$3 \nmid y_0, 3\|D, \text{ and } \frac{D}{3} \equiv -1 \pmod 3 \tag{4.5}$$

we have that if

$$(x_0 + y_0\sqrt{D})^{\frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell, y_0)}} = x_1 + y_1\sqrt{D}$$

then $n_3(y_1) = \max\{\ell, \ell_1\}$, $D^\ell \| y_1$, and $(x_1, y_1D^{-\ell})$ is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$.

(iii) In the case that $\ell_0 < \ell$ and Equation (4.5) does not hold, we have that if

$$(x_0 + y_0\sqrt{D})^{\frac{D^\ell}{\gcd(D^\ell, y_0)}} = x_1 + y_1\sqrt{D}$$

then $D^\ell \| y_1$ and $(x_1, y_1D^{-\ell})$ is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$.

Proof. Suppose $x_0 + y_0\sqrt{D}$ is the fundamental solution of $x^2 - Dy^2 = 1$ and $D^{\ell_0} \| y_0$. We write $y_0 = D^{\ell_0}ab$ for some $a, b \in \mathbb{N}$ with $\gcd(b, D) = 1$ and $p \mid D$ for any $p \mid a$.

(i) For $0 \leq \ell \leq \ell_0$, since

$$1 = x_0^2 - Dy_0^2 = x_0^2 - D^{2\ell+1}(D^{\ell_0-\ell}ab)^2$$

so $(x_0, D^{\ell_0-\ell}ab) = (x_0, y_0D^{-\ell}) \in \mathbb{N}^2$ is a solution of $x^2 - D^{2\ell+1}y^2 = 1$. We claim that $(x_0, y_0D^{-\ell})$ is the smallest such solution. Indeed, if $(s, t) \in \mathbb{N}^2$ is any solution of $x^2 - D^{2\ell+1}y^2 = 1$, then $(s, D^\ell t)$ is a solution of $x^2 - Dy^2 = 1$ and hence $s \geq x_0$

and $D^\ell t \geq y_0$ by the minimality of the fundamental solution. This implies that $t \geq y_0 D^{-\ell}$. Thus, $(x_0, y_0 D^{-\ell})$ is the minimal solution and hence the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$. This proves part (i).

(ii) Now, we consider the case in which $\ell > \ell_0$ and Equation (4.5) holds. We write

$$(x_0 + y_0\sqrt{D})^{\frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell,y_0)}} = x_1 + y_1\sqrt{D}.$$

Note that (x_1, y_1) is a solution of $x^2 - Dy^2 = 1$. By Lemma 3, we can write

$$(x_0 + y_0\sqrt{D})^{3^{\ell-\min\{\ell,\ell_1\}+1}} = x_0' + y_0'\sqrt{D}$$

with $n_3(y_0') = \ell - \min\{\ell, \ell_1\} + \ell_1 = \max\{\ell, \ell_1\}$ and $y_0' = 3^{\max\{\ell,\ell_1\}} y_0 z_0$ for some $z_0 \in \mathbb{N}$ with $3 \nmid z_0$. It follows from this and Lemma 5 that

$$\begin{aligned}
& (x_0 + y_0\sqrt{D})^{\frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell,y_0)}} \\
= & \left((x_0 + y_0\sqrt{D})^{3^{\ell-\min\{\ell,\ell_1\}+1}}\right)^{\frac{(D/3)^\ell}{\gcd(D^\ell,y_0)}} \\
= & \left(x_0' + y_0'\sqrt{D}\right)^{\frac{(D/3)^\ell}{\gcd(D^\ell,y_0)}} = x_1 + y_1\sqrt{D} \qquad (4.6)
\end{aligned}$$

with

$$y_1 = \frac{(D/3)^\ell}{\gcd(D^\ell, y_0)} y_0' y_2 = \left(\frac{D}{3}\right)^\ell 3^{\max\{\ell,\ell_1\}} \left(\frac{y_0}{\gcd(D^\ell, y_0)}\right) z_0 y_2$$

so that $D^\ell \mid y_1$ and $n_3(y_1) = n_3(y_0') = \max\{\ell, \ell_1\}$. So, we have that $(x_1, y_1 D^{-\ell})$ is a solution of $x^2 - D^{2\ell+1}y^2 = 1$. We claim that $(x_1, y_1 D^{-\ell})$ is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$. Suppose (s, t) is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$. Then,

$$x_1 + y_1\sqrt{D} = \left(s + tD^\ell\sqrt{D}\right)^N$$

for some $N \in \mathbb{N}$. On the other hand, $(s, tD^\ell) \in \mathbb{N}^2$ is a solution of $x^2 - Dy^2 = 1$, so

$$s + tD^\ell\sqrt{D} = (x_0 + y_0\sqrt{D})^M \qquad (4.7)$$

for some $M \in \mathbb{N}$. Therefore, we have

$$(x_0+y_0\sqrt{D})^{\frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell,y_0)}} = x_1+y_1\sqrt{D} = \left(s + tD^\ell\sqrt{D}\right)^N = (x_0+y_0\sqrt{D})^{NM}.$$

We will show that $N = 1$. Note that

$$M \mid \frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell, y_0)}. \qquad (4.8)$$

Using Equation (4.7) and Lemma 5, we have that $My_0y_2 = tD^\ell$. Again using Lemma 5, if $3 \nmid M$, then $3 \nmid y_0y_2$ which contradicts $3 \mid tD^\ell$. So, we have that $3 \mid M$.

Let M_1 be such that $M = 3^{n_3(M)}M_1$ and $3 \nmid M_1$. By Lemmas 3 and 5, we have

$$s + tD^\ell\sqrt{D} = (x_0 + y_0\sqrt{D})^{3^{n_3(M)}M_1} = (a + b\sqrt{D})^{M_1}$$

with $tD^\ell = M_1ay_2'$ where $n_3(a) = n_3(M) + \ell_1 - 1$ and $3 \nmid y_2'$. Hence

$$n_3(M_1ay_2') = n_3(a) = n_3(M) + \ell_1 - 1 \geq n_3(D)\ell = \ell \tag{4.9}$$

and furthermore

$$n_3\left(\frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell, y_0)}\right) = \ell - \min\{\ell, \ell_1\} + 1 \leq n_3(M)$$

by Equation (4.9).

For primes $p \mid D$ with $p \neq 3$, we use $My_0y_2 = tD^\ell$ with $\gcd(y_2, D) = 3$ from Equation (4.7) to get

$$n_p(M) + n_p(y_0) \geq n_p(D)\ell \tag{4.10}$$

and furthermore

$$\begin{aligned} n_p\left(\frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell, y_0)}\right) &= n_p\left(\frac{D^\ell}{\gcd(D^\ell, y_0)}\right) \\ &= n_p(D)\ell - \min\{n_p(D)\ell, n_p(y_0)\} \\ &\leq n_p(M) \end{aligned}$$

by Equation (4.10). Therefore, we have shown that any prime power that divides $\frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell,y_0)}$ divides M. Together with Equation (4.8), we conclude that

$$M = \frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell, y_0)}$$

and hence $N = 1$. Thus $(x_1, y_1D^{-\ell})$ is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$.

(iii) Now, we consider the case in which $\ell > \ell_0$ and Equation (4.5) does not hold. We write

$$(x_0 + y_0\sqrt{D})^{\frac{D^\ell}{\gcd(D^\ell, y_0)}} = x_1 + y_1\sqrt{D}.$$

Note that (x_1, y_1) is a solution of $x^2 - Dy^2 = 1$ and, by Lemma 5, $D^\ell \mid y_1$. So, we have that $(x_1, y_1D^{-\ell})$ is a solution of $x^2 - D^{2\ell+1}y^2 = 1$. We claim that $(x_1, y_1D^{-\ell})$

is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$. Suppose (s,t) is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$. Then, as in case (ii), we have

$$(x_0 + y_0\sqrt{D})^{\frac{D^\ell}{\gcd(D^\ell, y_0)}} = x_1 + y_1\sqrt{D} = \left(s + tD^\ell\sqrt{D}\right)^N = (x_0 + y_0\sqrt{D})^{NM}$$

for some $N, M \in \mathbb{N}$. Hence $\frac{D^\ell}{\gcd(D^\ell, y_0)} = NM$ and so $M \mid \frac{D^\ell}{\gcd(D^\ell, y_0)}$. Using Lemma 5, we may write $My_0y_2 = tD^\ell$ where $y_2 \in \mathbb{N}$ with $\gcd(y_2, D) = 1$. So, $M = \left(\frac{t}{y_0y_2}\right) D^\ell$. Since $\gcd(y_2, D) = 1$, we must have that $\frac{D^\ell}{\gcd(D^\ell, y_0)} \mid M$. We conclude that $M = \frac{D^\ell}{\gcd(D^\ell, y_0)}$, so $N = 1$ and $(x_1, y_1D^{-\ell})$ is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$. Additionally, we use Lemma 5 to get that $y_1 = \frac{D^\ell}{\gcd(D^\ell, y_0)} y_0y_2 = D^\ell \frac{y_0}{\gcd(D^\ell, y_0)} y_2$ with $\gcd(y_2, D) = 1$, so $D \nmid \frac{y_0}{\gcd(D^\ell, y_0)} y_2$ and thus $D^\ell \| y_1$. This proves part (iii). □

In view of Theorem 5, we are now able to evaluate $g(D^{2\ell+1})$ for sufficiently large ℓ.

Theorem 6. *Let $D > 2$ be a positive integer which is not a perfect square and $x_0 + y_0\sqrt{D}$ is the fundamental solution of $x^2 - Dy^2 = 1$. If Equation* (4.5) *does not hold and $\ell \geq \max\{\ell_0 + 1, n_p(y_0)/n_p(D) : p \mid D\}$, or Equation* (4.5) *holds and $\ell \geq \max\{\ell_0 + 1, \ell_1, n_p(y_0)/n_p(D) : p \mid D, p \neq 3\}$ where ℓ_0 and ℓ_1 are defined as in Theorem 5, then we have*

$$g(D^{2\ell+1}) = \begin{cases} D^{2\ell+1} & \text{if order}(x_0, D) = 1 \text{ and } D \text{ is odd,} \\ 2D^{2\ell+1} & \text{if order}(x_0, D) = 2 \text{ and } D \text{ is odd,} \\ D^{2\ell+1} & \text{if } D \text{ is even.} \end{cases}$$

Proof. Suppose Equation (4.5) does not hold and $\ell > \ell_0$. By Theorem 5, $\left(x_0 + y_0\sqrt{D}\right)^{\frac{D^\ell}{\gcd(D^\ell, y_0)}}$ is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$. In view of Lemma 5, we have

$$\left(x_0 + y_0\sqrt{D}\right)^{\frac{D^\ell}{\gcd(D^\ell, y_0)}} = x_1 + \frac{D^\ell}{\gcd(D^\ell, y_0)} y_0y_2\sqrt{D} = x_1 + y_1\sqrt{D^{2\ell+1}}.$$

with $y_1 = \frac{y_0y_2}{\gcd(D^\ell, y_0)}$ and $\gcd(y_2, D) = 1$. In view of Theorem 1, we need to evaluate $\text{order}(x_1, D^{2\ell+1})$ and $\frac{D^{2\ell+1}}{\gcd(D^{2\ell+1}, y_1)}$. So if $\ell \geq \frac{n_p(y_0)}{n_p(D)}$ for all $p \mid D$, then $\gcd\left(D^\ell, y_0\right) = y_0$ and $y_1 = y_2$. Hence $\gcd(y_1, D) = 1$. So $\frac{D^{2\ell+1}}{\gcd(D^{2\ell+1}, y_1)} = D^{2\ell+1}$.

Suppose Equation (4.5) holds and $\ell > \ell_0$. By Theorem 5, $\left(x_0 + y_0\sqrt{D}\right)^{\frac{D^\ell}{3^{\min\{\ell, \ell_1\}-1}\gcd(D^\ell, y_0)}}$ is the fundamental solution of $x^2 - D^{2\ell+1}y^2 = 1$. In the proof of (ii) of Theorem 5 and Equation (4.6), we have

$$(x_0 + y_0\sqrt{D})^{\frac{D^\ell}{3^{\min\{\ell, \ell_1\}-1}\gcd(D^\ell, y_0)}} = x_1 + y_1\sqrt{D^{2\ell+1}}$$

with
$$y_1 = 3^{\max\{\ell,\ell_1\}-\ell}\left(\frac{y_0}{\gcd(D^\ell, y_0)}\right) z_0 y_2$$
and $\gcd(D, z_0y_2) = 1$. So, if $\ell \geq \max\{\ell_1, n_p(y_0)/n_p(D) : p \mid D, p \neq 3\}$, then $\max\{\ell,\ell_1\} - \ell = 0$ and $\gcd\left(D^\ell, y_0\right) = y_0$. Hence $y_1 = z_0y_2$ and $\gcd\left(D^{2\ell+1}, y_1\right) = 1$. It follows that $\frac{D^{2\ell+1}}{\gcd(D^{2\ell+1},y_1)} = D^{2\ell+1}$.

We now consider $\mathrm{order}(x_1, D^{2\ell+1})$. If D is odd, then we claim that $\mathrm{order}(x_1, D^{2\ell+1}) = \mathrm{order}(x_0, D)$, equivalently, $x_1 \equiv 1 \pmod{D^{2\ell+1}}$ if and only if $x_0 \equiv 1 \pmod{D}$. Indeed, if $x_1 \equiv 1 \pmod{D^{2\ell+1}}$, then by Theorem 3 (ii) we have $x^2 - D^{2\ell+1}y^2 = 2$ is solvable. Thus $x^2 - Dy^2 = 2$ is also solvable and hence $x_0 \equiv 1 \pmod{D}$. Conversely, suppose $x_0 \equiv 1 \pmod{D}$. Since from the proof of Lemma 5, we have
$$x_1 = \sum_{0\leq j\leq M/2} \binom{M}{2j} x_0^{M-2j} y_0^{2j} D^j \equiv x_0^M \pmod{D}$$
with $M = \frac{D^\ell}{\gcd(D^\ell,y_0)}$ or $M = \frac{D^\ell}{3^{\min\{\ell,\ell_1\}-1}\gcd(D^\ell,y_0)}$, so $x_1 \equiv 1 \pmod{D}$. Note that x_1 is a solution of the congruence equation $x^2 \equiv 1 \pmod{D^{2\ell+1}}$. For any odd prime p such that $p^r \| D$, x_1 is a solution of the congruence equation $x^2 \equiv 1 \pmod{p^{r(2\ell+1)}}$ and $x \equiv 1 \pmod{p^r}$. In view of Theorem 5.30 of [4], we can uniquely lift x_1 from a solution of $x^2 \equiv 1 \pmod{p^r}$ to a solution a of
$$\begin{cases} x^2 \equiv 1 \pmod{p^{r+1}} \\ x \equiv 1 \pmod{p^r}. \end{cases} \tag{4.11}$$
Thus, $a \equiv 1 \pmod{p^{r+1}}$. Since x_1 is also a solution of the equations in Equation (4.11), we must also have that $x_1 \equiv 1 \pmod{p^{r+1}}$. Inductively, $x_1 \equiv 1 \pmod{p^{r(2\ell+1)}}$. By the Chinese remainder theorem, $x_1 \equiv 1 \pmod{D^{2\ell+1}}$. This proves the claim.

Suppose D is even. Since $\ell \geq 1$, we have that $x^2 - D^{2\ell+1}y^2 = 2$ is not solvable by Lemma 2 because $D \neq 2d$ with odd d. Hence $x_1 \not\equiv 1 \pmod{D^{2\ell+1}}$ and so $\mathrm{order}(x_1, D^{2\ell+1}) = 2$.

Therefore
$$\begin{aligned} g(D^{2\ell+1}) &= \mathrm{lcm}\left(\mathrm{order}(x_1, D^{2\ell+1}), \frac{D^{2\ell+1}}{\gcd\left(D^{2\ell+1}, y_1\right)}\right) \\ &= \begin{cases} \mathrm{lcm}\left(\mathrm{order}(x_0, D), D^{2\ell+1}\right) & \text{if } D \text{ is odd,} \\ \mathrm{lcm}\left(2, D^{2\ell+1}\right) & \text{if } D \text{ is even,} \end{cases} \\ &= \begin{cases} D^{2\ell+1} & \text{if } \mathrm{order}(x_0, D) = 1 \text{ and } D \text{ is odd,} \\ 2D^{2\ell+1} & \text{if } \mathrm{order}(x_0, D) = 2 \text{ and } D \text{ is odd,} \\ D^{2\ell+1} & \text{if } D \text{ is even.} \end{cases} \end{aligned}$$

This completes the proof of the theorem. □

Corollary 4. *Let p be an odd prime. If $p^{\ell_0}\|y_0$, then*

$$g(p^{2\ell+1}) = \begin{cases} p^{2\ell+1-\min\{\ell_0-\ell,2\ell+1\}} & \text{if } p \equiv 7 \pmod 8, \\ 2p^{2\ell+1-\min\{\ell_0-\ell,2\ell+1\}} & \text{if } p \not\equiv 7 \pmod 8, \end{cases}$$

for $0 \le \ell \le \ell_0$. For $\ell > \ell_0$, we have

$$g(p^{2\ell+1}) = \begin{cases} p^{2\ell+1} & \text{if } p \equiv 7 \pmod 8, \\ 2p^{2\ell+1} & \text{if } p \not\equiv 7 \pmod 8. \end{cases}$$

In many of the proofs found in this section, we considered the binomial expansion of

$$(x_0 + y_0\sqrt{D})^n = x_n + y_n\sqrt{D}$$

for various $n \ge 1$ in order to establish congruence properties for x_n and y_n modulo D. We now touch upon a potential alternative method to obtain the same results. We define

$$x_{-1} = 2, \quad y_{-1} = 0, \quad u_n = \frac{y_n}{y_0}, \quad v_n = 2x_n.$$

It is known that x_n, y_n, u_n, and v_n are Lucas sequences, satisfying

$$\sigma_n = 2x_1\sigma_{n-1} - \sigma_{n-2}$$

for all $n > 0$, where σ is any of x, y, u, v. There are many divisibility properties known about Lucas sequences. For some of the many identities known for x_n, y_n, u_n, v_n, see [10].

For certain D, perhaps it is possible to determine $\gcd(y_0, D)$, thus simplifying the formula for $g(D)$ given in Theorem 1. Of course, a proof of the AAC and Mordell conjectures would resolve the case for prime D. A related notion is the *rank of apparition of k in $\{y_n\}$*, which is to say the smallest n such that $k \mid y_n$, around which there is much literature. In the same vein, we have the following result due to Lehmer (Theorem 7 in [10] and Theorem 2.2 in [11]):

Let $p \mid D$ be prime. Then $p \nmid y_0$ if and only if $\displaystyle\prod_{i=0}^{p-2} y_i \equiv -\left(\frac{x_0}{p}\right) \pmod p$.

This is a potentially useful result for proving more explicit versions of Theorem 1 for certain D.

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D	Fundamental Solution Order	order(x_0, D)	$g(D)$
3	$2 + \sqrt{3}$	2	6
5	$9 + 4\sqrt{5}$	2	10
11	$10 + 3\sqrt{11}$	2	22
13	$649 + 180\sqrt{13}$	2	26
15	$4 + \sqrt{4.6}$	2	30
17	$33 + 8\sqrt{17}$	2	34
19	$170 + 39\sqrt{4.7}$	2	38
27	$26 + 5\sqrt{27}$	2	54
29	$9801 + 1820\sqrt{29}$	2	58
33	$23 + 4\sqrt{33}$	2	66
35	$6 + \sqrt{35}$	2	70
37	$73 + 12\sqrt{37}$	2	74
39	$25 + 4\sqrt{39}$	2	78
41	$2049 + 320\sqrt{41}$	2	82
43	$3482 + 531\sqrt{43}$	2	86
51	$50 + 7\sqrt{51}$	2	102
53	$66249 + 9100\sqrt{53}$	2	106
55	$89 + 12\sqrt{55}$	2	110
57	$151 + 20\sqrt{57}$	2	114
59	$530 + 69\sqrt{59}$	2	118
61	$1766319049 + 226153980\sqrt{61}$	2	122
63	$8 + \sqrt{63}$	2	126
65	$129 + 16\sqrt{65}$	2	130
67	$8842 + 5967\sqrt{67}$	2	134
73	$2281249 + 267000\sqrt{73}$	2	146
77	$351 + 40\sqrt{77}$	2	154
83	$82 + 9\sqrt{83}$	2	166
85	$285769 + 30996\sqrt{85}$	2	170
89	$500001 + 53000\sqrt{89}$	2	178
91	$1574 + 165\sqrt{91}$	2	182
95	$39 + 4\sqrt{95}$	2	190
97	$62809633 + 6377352\sqrt{97}$	2	194
99	$10 + \sqrt{99}$	2	198

Table 1: $3 \leq D \leq 100$, and D is not a perfect square and $g(D) = 2D$

D	Fundamental Solution Order	order(x_0, D)	$g(D)$
6	$5+2\sqrt{6}$	2	6
7	$8+3\sqrt{7}$	1	7
8	$3+\sqrt{8}$	2	8
10	$19+6\sqrt{10}$	2	10
18	$17+4\sqrt{4.6}$	2	18
22	$197+42\sqrt{22}$	2	22
23	$24+5\sqrt{23}$	1	23
24	$5+\sqrt{24}$	2	24
26	$51+10\sqrt{26}$	2	26
30	$11+2\sqrt{4.9}$	2	30
31	$1520+273\sqrt{31}$	1	31
32	$17+3\sqrt{32}$	2	32
38	$37+6\sqrt{38}$	2	38
40	$19+3\sqrt{40}$	2	40
42	$13+2\sqrt{42}$	2	42
47	$48+7\sqrt{47}$	1	47
48	$7+\sqrt{48}$	2	48
50	$99+14\sqrt{50}$	2	50
58	$19603+2574\sqrt{58}$	2	58
66	$65+8\sqrt{66}$	2	66
71	$3480+413\sqrt{71}$	1	71
74	$3699+430\sqrt{74}$	2	74
79	$80+9\sqrt{79}$	1	79
80	$9+\sqrt{80}$	2	80
82	$163+18\sqrt{82}$	2	82
86	$10405+1122\sqrt{86}$	2	86
88	$197+21\sqrt{88}$	2	88
90	$19+2\sqrt{90}$	2	90
96	$49+5\sqrt{96}$	2	96

Table 2: $2 \leq D \leq 100$, and D is not a perfect square and $g(D) = D$

D	Fundamental Solution Order	order(x_0, D)	$g(D)$
2	$3 + 2\sqrt{2}$	1	1
12	$7 + 2\sqrt{12}$	2	6
14	$15 + 4\sqrt{14}$	1	7
20	$9 + 2\sqrt{20}$	2	10
28	$127 + 24\sqrt{28}$	2	14
34	$35 + 6\sqrt{34}$	1	17
44	$199 + 30\sqrt{44}$	2	22
52	$649 + 90\sqrt{52}$	2	26
56	$15 + 2\sqrt{56}$	2	28
60	$31 + 4\sqrt{60}$	2	30
62	$63 + 8\sqrt{62}$	1	31
68	$33 + 4\sqrt{68}$	2	34
72	$17 + 2\sqrt{72}$	2	36
76	$57799 + 6630\sqrt{76}$	2	38
92	$1151 + 120\sqrt{92}$	2	46
94	$2143295 + 221064\sqrt{94}$	1	47
98	$99 + 10\sqrt{98}$	1	49

Table 3: $2 \leq D \leq 100$, and D is not a perfect square and $g(D) = D/2$

D	Fundamental Solution Order	order(x_0, D)	$g(D)$
46	$24335 + 3588\sqrt{46}$	1	1
54	$485 + 66\sqrt{54}$	2	18
70	$251 + 30\sqrt{70}$	2	14
78	$53 + 6\sqrt{78}$	2	26
84	$55 + 6\sqrt{84}$	2	14

Table 4: $2 \leq D \leq 100$, and D is not a perfect square and $g(D) < D/2$