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$D(-1)$-QUADRUPLES AND PRODUCTS OF TWO PRIMES

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Abstract. A $D(-1)$-quadruple is a set of positive integers $\{a, b, c, d\}$, with $a < b < c < d$, such that the product of any two elements from this set is of the form $1 + n^2$ for some integer n. Dujella and Fuchs showed that any such $D(-1)$-quadruple satisfies $a = 1$. The $D(-1)$ conjecture states that there is no $D(-1)$-quadruple. If $b = 1 + r^2, c = 1 + s^2$ and $d = 1 + t^2$, then it is known that r, s, t, b, c and d are not of the form p^k or $2p^k$, where p is an odd prime and k is a positive integer. In the case of two primes, we prove that if $r = pq$ and v and w are integers such that $p^2v - q^2w = 1$, then $4vw - 1 > r$. A particular instance yields the result that if $r = p(p + 2)$ is a product of twin primes, where $p \equiv 1 \pmod 4$, then the $D(-1)$-pair $\{1, 1 + r^2\}$ cannot be extended to a $D(-1)$-quadruple. Dujella's conjecture states that there is at most one solution (x, y) in positive integers with $y < k - 1$ to the diophantine equation $x^2 - (1 + k^2)y^2 = k^2$. We show that the Dujella conjecture is true when k is a product of two odd primes. As a consequence it follows that if t is a product of two odd primes, then there is no $D(-1)$-quadruple $\{1, b, c, d\}$ with $d = 1 + t^2$.

1. Introduction

Let n be a nonzero integer. A diophantine m-tuple with the property $D(n)$, is a set of m positive integers, such that if a, b are any two elements from this set, then $ab + n = k^2$ for some integer k. We will look at the case $n = -1$. The cases $n = 1$ and $n = 4$ have been studied in great detail and still continue to be areas of active research. For more details on this subject the reader may consult [1], where a comprehensive and up to date list of references is available.

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In the case of $n = -1$, it has been conjectured that there is no $D(-1)$-quadruple. The first significant progress was made by Dujella and Fuchs ([2]), who showed that if $\{a, b, c, d\}$ is a $D(-1)$-quadruple with $a < b < c < d$, then $a = 1$. Subsequently, Dujella et. al. ([3]) proved that there are only a finite number of such quadruples. Filipin and Fujita ([4]) showed that if $\{1, b, c\}$ is $D(-1)$-triple with $b < c$, then there exist at most two d's such that $\{1, b, c, d\}$ is a $D(-1)$-quadruple.

Filipin, Fujita and Mignotte ([5]) showed that if $b = r^2 + 1$, then in each of the cases $r = p^k$, $r = 2p^k$, $b = p$ and $b = 2p^k$, where p is an odd prime and k is a positive integer, the $D(-1)$-pair $\{1, b\}$ cannot be extended to a $D(-1)$-quadruple $\{1, b, c, d\}$ with $b < c < d$. In [13] we showed that this also holds for $c = 1 + s^2$, that is, if $s = p^k$, $s = 2p^k$, $c = p$ or $c = 2p^k$, then the $D(-1)$-triple $\{1, b, c\}$ cannot be extended to a $D(-1)$-quadruple (one of the referees pointed out that this result was essentially proved in [5]). It is also known that the results mentioned above for b and c also hold for $d = 1 + t^2$ (see discussion following Conjecture 1.3). Note that b, c and d cannot be of the form p^k with $k > 1$ and p prime (see [8]). In the case of a product of two primes, we showed in [13] that if $r = pq$ then $p^4, q^4 > r$. The following result gives further conditions in this case.

THEOREM 1.1. *Let $\{1, b, c, d\}$ with $1 < b < c < d$ be a $D(-1)$-quadruple with $b = 1+r^2$ where $r > 0$. Let $r = pq$, where p and q are distinct odd primes, and let v and w be integers such that $p^2v - q^2w = 1$. Then $4vw - 1 > r$.*

COROLLARY 1.2. *Let $b = 1 + r^2$ and $r = p(p + 2)$ where p and $p + 2$ are both primes and $p \equiv 1 \pmod 4$. Then the $D(-1)$-pair $\{1, b\}$ cannot be extended to a $D(-1)$-quadruple.*

The following conjecture made by Andrej Dujella is closely related to the $D(-1)$ conjecture.

CONJECTURE 1.3. (Andrej Dujella) *Let $k \geq 2$. Then there exists at most one solution (x, y) in positive integers to the equation $x^2 - (k^2 + 1)y^2 = k^2$ with $y < k - 1$.*

In [9] the authors studied the equation $x^2 - (k^2 + 1)y^2 = k^2$, calling it the Dujella equation and the conjecture above, which they called the unicity conjecture. They used a continued fraction approach and gave some interesting equivalent conjectures.

It is known that Dujella's unicity conjecture implies the $D(-1)$ conjecture (see [9, Section 17]). Indeed the result [5] on the $D(-1)$ conjecture mentioned above, is based on [5, Lemma 6.1], which states that Conjecture 1.3 is true for the same cases, namely, when $k^2 + 1 = p, 2p^n$, or $k = p^n, 2p^n$, where p is an odd prime and n is a positive integer. It follows, also from [5, Lemma 6.1], that the $D(-1)$ conjecture holds in the case when t or $d = 1 + t^2$ is of the form p^n or $2p^n$, where p is an odd prime and k is a positive integer.

K. Matthews communicated to the author an unpublished short proof (along with J. Robertson) of Conjecture 1.3 in the case when k^2+1 is divisible by exactly two odd primes. We show that Conjecture 1.3 is true when k is a product of two odd primes.

THEOREM 1.4. *Let $k = pq$ where p and q are distinct odd primes. Then the equation $x^2 - (1+k^2)y^2 = k^2$ has at most one solution (x, y) in positive integers with $y < k-1$.*

An immediate corollary is the following.

COROLLARY 1.5. *If x is a product of two distinct odd primes and $d = 1+x^2$, then there is no $D(-1)$-quadruple $\{1, b, c, d\}$ with $1 < b < c < d$.*

2. Binary quadratic forms

In this section we present the basic theory of binary quadratic forms. An excellent reference is [11], where Sections 4 to 7 and Section 11 of Chapter 6 pertain to the matter at hand.

A *primitive binary quadratic form* $f = (a, b, c)$ of discriminant d is a function $f(x, y) = ax^2 + bxy + cy^2$, where a, b, c are integers with $b^2 - 4ac = d$ and $\gcd(a, b, c) = 1$. Note that the integers b and d have the same parity. All forms considered here are primitive binary quadratic forms and henceforth we shall refer to them simply as forms.

Two forms f and f' are said to be *equivalent*, written as $f \sim f'$, if for some $A = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \in SL_2(\mathbb{Z})$ (called a transformation matrix), we have $f'(x, y) = f(\alpha x + \beta y, \gamma x + \delta y) = (a', b', c')$, where a', b', c' are given by

$$a' = f(\alpha, \gamma), \quad b' = 2(a\alpha\beta + c\gamma\delta) + b(\alpha\delta + \beta\gamma), \quad c' = f(\beta, \delta). \tag{2.1}$$

It is easy to see that $\sim$ is an equivalence relation on the set of forms of discriminant d. The equivalence classes form an abelian group called the *class group* with group law given by composition of forms. The *identity form* is defined as the form $(1, 0, \frac{-d}{4})$ or $(1, 1, \frac{1-d}{4})$, depending on whether d is even or odd respectively. The *inverse* of $f = (a, b, c)$ denoted by f^{-1}, is given by $(a, -b, c)$.

A form f is said to represent an integer m if there exist integers x and y such that $f(x, y) = m$. If $\gcd(x, y) = 1$, we call the representation a primitive one. Observe that equivalent forms primitively represent the same set of integers, as do a form and its inverse. Hence, sometimes we will refer to a class of forms that represents an integer.

We end this section with two elementary observations about forms. Firstly, if a form f represents primitively an integer n, then $f \sim (n, b, c)$ for some integers b, c. This follows simply by noting that if $f(\alpha, \gamma) = n$ with $\gcd(\alpha, \gamma) = 1$, then there exists a transformation matrix A as given above such that (2.1) holds. Secondly, if $b \equiv b' \pmod{2n}$, then the forms (n,b,c) and (n,b',c') are equivalent. This equivalence follows using the transformation matrix $A = \begin{pmatrix} 1 & \delta \\ 0 & 1 \end{pmatrix}$ where $b' = b + 2n\delta$.

3. The diophantine equation $x^2 - dy^2 = n$

For any positive integer d that is not a square, all representations (x,y) of an integer n by the form $(1,0,-d)$ may be put into equivalence classes using the following notion of equivalence.

Definition 3.1. *Two solutions (x,y) and (x',y') of $X^2 - dY^2 = n$ are said to be equivalent, written as $(x,y) \sim (x',y')$ if the following congruences*

$$xx' \equiv dyy' \pmod{n}, \quad xy' \equiv yx' \pmod{n} \tag{3.1}$$

are satisfied.

The result given below is used at several places, and hence we isolate it as a lemma.

Lemma 3.2. *Let k be an odd integer. If a solution (x,y) of the equation $x^2 - (1+k^2)y^2 = k^2$ satisfies $(x,y) \sim (x,-y)$, then k divides x and y.*

Proof. If $(x,y) \sim (x,-y)$, then (3.1) gives $x^2 \equiv -y^2 \pmod{k^2}$. Moreover, from the Dujella equation, $x^2 \equiv y^2 \pmod{k^2}$, hence k divides x and y. ∎

The following lemma connects primitive representations of $x^2 - dy^2 = n$ and forms that represent n and is crucial for our proofs.

Lemma 3.3. *Let n be a positive integer such that $\gcd(n, 2\Delta) = 1$ and suppose that n is primitively represented by some form of discriminant Δ. Then the following claims hold.*

1. *If $A = \{(n,b,c); 0 < b < 2n\}$ and $w(n)$ is the number of distinct primes dividing n, then $|A| = 2^{w(n)}$.*
2. *There is a one-to-one correspondence between the set of equivalence classes of primitive solutions (x,y) of the equation $X^2 - dY^2 = n$ and the set $A_0 = \{(n,b,c) \sim (1,0,-d); 0 < b < 2n\}$ of forms in A equivalent to the identity form.*

Proof. As n is primitively represented by some form of discriminant Δ, there is a solution to the congruence $\Delta \equiv x^2 \pmod{4n}$ ([11, Solution of problem 1]). It follows from a classical result (see for instance [14, Chapter V, §4] or [7, Theorem 122]) that there are $2^{w(n)+1}$ solutions modulo $4n$. As x and $-x$ are both solutions to $\Delta \equiv x^2 \pmod{4n}$, there are $2^{w(n)}$ solutions to the congruence $\Delta \equiv x^2 \pmod{4n}$ with $0 < x < 2n$. The first part of the lemma now follows from [11, Solution of problem 2], where it is shown that there is a one-to-one correspondence between the set A and solutions to the congruence $\Delta \equiv x^2 \pmod{4n}$ with $0 < x < 2n$.

The second part of the lemma follows from the following facts that are given in [11, Solution of problem 3]. Each primitive representation (x, y) of $X^2 - dY^2 = n$ corresponds to a unique form (n, b, c), where $0 < b < 2n$. If two such representations correspond to the same form, then the representations are equivalent. Moreover, each form in set A_0 corresponds to a unique equivalence class of primitive representations (x, y) of $X^2 - dY^2 = n$, and hence the correspondence in part 2 of the lemma follows. $\square$

The next lemma has been used by several authors in the study of the current problem, such as [5, Lemma 6.2] and [13, Lemma 3.2].

LEMMA 3.4 ([6, Lemma 2.3]). *Let n be an integer such that $1 < |n| \leq k$. Then there are no primitive solutions (x, y) such that $x^2 - (k^2 + 1)y^2 = n$.*

A useful consequence of the above lemma is the following result.

LEMMA 3.5 ([13, Lemma 3.3]). *Let $k = ff'$ be a positive integer such that $1 < f < k$. If $x^2 - (k^2 + 1)y^2 = f'^2$ for some coprime integers x and y, then f' is not an odd prime power.*

4. PROOFS

Throughout this section the following terminology will be used.

Let $\{1, b, c, d\}$ be a $D(-1)-$quadruple with $1 < b < c < d$. Set

$$b = 1 + r^2, \quad c = 1 + s^2, \quad d = 1 + x^2$$

and

$$bd = 1 + y^2, \quad cd = 1 + z^2, \quad bc = 1 + t^2.$$

Then

$$t^2 - (1 + r^2)s^2 = r^2 \tag{4.1}$$

and

$$t^2 - (1 + s^2)r^2 = s^2. \tag{4.2}$$

It is easy to see (using (3.1)) that the equation $X^2 - (r^2 + 1)Y^2 = r^2$ has the inequivalent solutions $(r, 0)$ and $(r^2 + 1 - r, \pm(r - 1))$. In [5], solutions equivalent to these three solutions were called regular solutions and it was shown that (t, s) is not a regular solution.

LEMMA 4.1 ([5, Corollary 1.2]). *The solution (t, s) of $X^2 - bY^2 = r^2$ is not equivalent to any of the solutions $(b - r, \pm(r - 1))$ and $(r, 0)$.*

LEMMA 4.2. *Let $r = pq$ where p and q are distinct odd primes. Then there are exactly four inequivalent classes of primitive representations of r^2 by the form $(1, 0, -(1 + r^2))$, namely, $(b - r, \pm(r - 1))$ and $(t, \pm s)$. Moreover, r^2 is primitively represented only by the identity class.*

Proof. Let $\gcd(t,s)=n$. As $r=pq$, from (4.1) we have $n=1,r,p$ or q. Observe that by Lemma 3.5 the cases $n=p$ and $n=q$ are not possible. If $n=r$, then t and s are divisible by r. It follows by equivalence of solutions (Definition 3.1) that $(t,s)\sim(r,0)$, which is not possible by Lemma 4.1. Hence $\gcd(t,s)=1$, and it follows from Lemma 3.2 and Lemma 4.1 that $(b-r,\pm(r-1))$ and $(t,\pm s)$ are inequivalent primitive representations. By Lemma 3.3, the set A_0 (given therein) has at least 4 elements. Moreover, by the same lemma, the set A has exactly 4 elements and therefore $A=A_0$ as $A_0\subseteq A$ and hence there are exactly four inequivalent classes of primitive representations of r^2 by $(1,0,-b)$, namely the ones given above. ∎

The second part of the following lemma follows on application of [12, Theorem 1] (a converse to Nagell's theorem). However, the article mentioned above only provides an outline of the proof and we are grateful to a referee for the details given below.

Lemma 4.3. *Let $k=pq$, where p and q are distinct odd primes. Then the following hold.*

1. *Any solution (α,β) of $X^2-(1+k^2)Y^2=k^2$ with $0<\beta<k$ satisfies $\gcd(\alpha,\beta)=1$.*
2. *Let (x,y) and (x',y') be two equivalent solutions in positive integers to $X^2-(1+k^2)Y^2=k^2$ that satisfy $y,y'<k-1$. Then $x=x'$ and $y=y'$.*

Proof. As seen in the beginning of the proof of Lemma 4.2, either $\gcd(\alpha,\beta)=1$ or k divides both α and β, the latter of which is not possible as $0<\beta<k$ and hence $\gcd(\alpha,\beta)=1$.

For the second part, observe that $(2k^2+1,2k)$ is the fundamental solution of the Pell equation $X^2-(1+k^2)Y^2=1$. It is well known (see for example [12]) that if (x,y) and (x',y') are equivalent, then

$$x'+y'\sqrt{d}=\pm(x+y\sqrt{d})(2k^2+1+2k\sqrt{d})^n, \tag{4.3}$$

for some integer n. Since $x^2-dy^2=k^2$, we may rewrite (4.3) as

$$(x'+y'\sqrt{d})(x-y\sqrt{d})=\pm k^2(2k^2+1+2k\sqrt{d})^n=A+B\sqrt{d}. \tag{4.4}$$

It is easy to see that $2k^3$ divides B in the above equation and hence it also divides $xy'-yx'$. Observe that since y and y' are positive integers less than $k-1$, it follows from the Dujella equation that x and x' are less than k^2-k+1. Hence, as $xy'-yx'$ is divisible by $2k^3$, we have $xy'=yx'$, which gives $x=x'$ and $y=y'$, since from part one of the lemma $\gcd(x,y)=\gcd(x',y')=1$. ∎

Proof of Theorem 1.1. Let v and w be integers such that $vp^2-wq^2=1$ and let h be the form $(r^2,4q^2w+2,4vw-1)$, where $r=pq$. It is straightforward to see that h is a form of discriminant $4b$ and that $4vw-1>0$. Moreover, h primitively represents r^2 and thus, by Lemma 4.2, we have $h\sim(1,0,-b)$.

Furthermore, h also primitively represents $4vw-1$ and hence, by Lemma 3.4, we have $4vw-1>r$. ◻

PROOF OF COROLLARY 1.2. Note that if $v=\frac{p+3}{4}$ and $w=\frac{p-1}{4}$, then we have $vp^2-w(p+2)^2=1$. Moreover, $4vw-1=(p+3)\frac{p-1}{4}-1<p(p+2)$ and the corollary follows from Theorem 1.1. ◻

PROOF OF THEOREM 1.4. Let (x,y) be a solution of the Dujella equation $x^2-(1+k^2)y^2=k^2$, with $x,y>0$ and $y<k-1$. Then $x=|x|<k^2-k+1$ and $0<x+y<k^2$. Now suppose that $(x,y)\sim(1+k^2-k,\pm(k-1))$. Then (3.1) gives

$$x \equiv \pm y \pmod{k^2}, \tag{4.5}$$

which is not possible, as we have shown above that $0<x+y<k^2$. Therefore (x,y) is not equivalent to either of the solutions $(1+k^2-k,\pm(k-1))$. Furthermore, using Lemma 3.2 and Lemma 4.3, part 1, it follows that the solutions $(x,\pm y)$ and $(1+k^2-k,\pm(k-1))$ are inequivalent primitive solutions. Therefore $|A_0|\geq 4$, where A_0 is as given in Lemma 3.3. From the same lemma we have $|A|=4$ and as $A_0\subseteq A$ it follows that $A_0=A$. Thus there are exactly four inequivalent classes of primitive solutions, namely the classes represented by $(x,\pm y)$ and $(1+k^2-k,\pm(k-1))$. Now, if (x',y') is another solution in positive integers to the Dujella equation satisfying $y'<k-1$, then it must be equivalent to one of $(x,\pm y)$ (since we have shown above that any such solution is not equivalent to $(1+k^2-k,\pm(k-1))$). From Lemma 4.3 part 2, we have $(x,y)=(x',y')$, and hence there is at most one solution in positive integers (x,y) with $y<k-1$ to the equation $X^2-(1+k^2)Y^2=k^2$, and the theorem is proved. ◻

PROOF OF COROLLARY 1.5. By Theorem 1.4, if x is a product of two distinct odd primes, then the equation $\alpha^2-(1+x^2)\beta^2=x^2$ has at most one positive solution (α,β) with $\beta<x-1$. In other words, the Dujella conjecture holds for this equation and as shown in [9, Section 17], this implies that the $D(-1)$ conjecture is true. ◻

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