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# Square-free values of $n^2+1$

by

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*To Professor Andrzej Schinzel*
*in celebration of his seventy-fifth birthday*

**1. Introduction.** Let $\mathcal{N}(x)$ denote the number of positive integers $n \le x$ for which $n^2+1$ is square-free. It was shown in 1931 by Estermann [4] that

$$\mathcal{N}(x) = c_0 x + O(x^{2/3}\log x)$$

for $x \ge 2$, where

$$c_0 = \frac{1}{2}\prod_{p\equiv 1 \bmod 4}(1-2p^{-2}).$$

Estermann's argument is very simple, but despite the passage of 80 years the exponent $2/3$ appearing above has never been improved. The aim of the present paper is to establish the following result.

Theorem. *We have*

$$\mathcal{N}(x) = c_0 x + O_\varepsilon(x^{7/12+\varepsilon})$$

*for any fixed* $\varepsilon > 0$.

It is easy to construct intervals $(x, x+c\log x]$ with a small positive constant $c$, such that $n^2+1$ has a non-trivial square factor for every $n$ in the interval. This shows that the error term in our theorem is $\Omega(\log x)$. However we know of no better result of this type, and it is unclear what one should conjecture. With the much simpler problem of the number of square-free integers $n \le x$ one has an easy error term $O(x^{1/2})$, but any reduction in the exponent $1/2$ would appear to require a quasi Riemann Hypothesis. Thus it seems unlikely that we could reduce the exponent in our theorem below $1/2$ without a radically new idea.

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The key point in our treatment will be to give good upper bounds for the frequency of solutions to the Diophantine equation $d^2e = n^2+1$. Analysing this over $\mathbb{Q}(i)$ we are led to study the condition $2x_1x_2y_1 + (x_1^2 - x_2^2)y_2 = 1$, which we may interpret as saying that the point $(s,t) = (x_1/x_2, y_1/y_2)$ lies close to the curve $t = (1-s^2)/(2s)$. In order to study this we we will use a variant of the "Determinant Method", developed from the author's papers [5], [6].

The author was introduced to this problem by Dr Tim Browning. His contributions to the resulting discussions, and his careful proof-reading of the present paper, are gratefully acknowledged.

**2. Preliminaries.** For the proof it will clearly suffice to show that

$$\mathcal{N}(2x) - \mathcal{N}(x) = c_0 x + O_\varepsilon(x^{7/12+\varepsilon}).$$

The argument begins by observing that for $x \geq 1$ and $1 \leq D \leq x$ we have

$$\begin{aligned}
(1)\qquad \mathcal{N}(2x) - \mathcal{N}(x) &= \sum_{x<n\leq 2x} \mu^2(n^2+1) = \sum_{x<n\leq 2x}\ \sum_{d^2|n^2+1} \mu(d) \\
&= \sum_{d\leq 4x} \mu(d)\#\{x<n\leq 2x : d^2 \mid n^2+1\} \\
&= \sum_{d\leq D} \mu(d)\#\{x<n\leq 2x : d^2 \mid n^2+1\} \\
&\qquad + O\Big(\sum_{D<d\leq 4x} \#\{x<n\leq 2x : d^2 \mid n^2+1\}\Big).
\end{aligned}$$

For $d \leq D$ we write

$$\rho(d) = \rho = \#\{m \bmod d^2 : d^2 \mid m^2+1\},$$

and we take $m_1, \ldots, m_\rho$ to be a corresponding set of admissible values for $m$. Then

$$\begin{aligned}
(2)\qquad \#\{x<n\leq 2x : d^2 \mid n^2+1\} &= \sum_{j=1}^{\rho} \#\{x<n\leq 2x : n\equiv m_j \bmod d^2\} \\
&= \sum_{j=1}^{\rho}\left(\frac{x}{d^2} + O(1)\right) = x\frac{\rho(d)}{d^2} + O(\rho(d)).
\end{aligned}$$

Thus terms with $d \leq D$ contribute to (1) a total

$$x\sum_{d\leq D} \mu(d)\rho(d)d^{-2} + O\Big(\sum_{d\leq D}\rho(d)\Big).$$

The function $\rho(d)$ is multiplicative, with $\rho(p) = 2$ for $p \equiv 1 \bmod 4$ and $\rho(p) = 0$ for other odd $p$. Thus $\rho(d)$ is bounded by the $r(d)$ function which counts representations as sums of two squares. We therefore see that

$$\sum_{E<d\le 2E}\rho(d)\ll E$$

for any integer $E$, whence

$$\sum_{d>D}|\mu(d)\rho(d)d^{-2}|\ll D^{-1}\quad\text{and}\quad\sum_{d\le D}\rho(d)\ll D.$$

The contribution to (1) corresponding to values $d\le D$ is therefore

$$x\sum_{d=1}^{\infty}\frac{\mu(d)\rho(d)}{d^2}+O(xD^{-1})+O(D).$$

Since

$$\sum_{d=1}^{\infty}\frac{\mu(d)\rho(d)}{d^2}=\prod_p(1-\rho(p)p^{-2})$$

we see that this produces the main term in our theorem. We will minimize the other error terms by choosing $D=x^{1/2}$.

To handle the larger values of $d$ we consider dyadic ranges $E/2<d\le E$, and write

$$\mathcal{M}(E,F)=\#\{(e,f,n)\in\mathbb{N}^3: E/2<e\le E,\ F/2<f\le F,\ e^2f=n^2+1\}.$$

Then the range $d>D$ contributes to (1) a total

$$\ll\sum_{E\gg D}\max_{x^2E^{-2}\ll F\ll x^2E^{-2}}\mathcal{M}(E,F),$$

where the summation for $E$ runs over powers of 2. Thus our problem reduces to one of estimating $\mathcal{M}(E,F)$ efficiently. Heuristically one might expect that $e^2f-1$ is a square "with probability" of order $(e^2f)^{-1/2}$. This leads one to conjecture that the true order of magnitude for $\mathcal{M}(E,F)$ might be about $F^{1/2}$. For his proof, Estermann showed that

$$\#\{(e,n)\in\mathbb{N}^2: E/2<e\le E,\ e^2f=n^2+1\}\ll\log x,\tag{3}$$

whence $\mathcal{M}(E,F)\ll F\log x$. One easily sees how this leads to the error term $O(x^{2/3}\log x)$. We will need sharper bounds, but we note that Estermann's estimate shows that the range $F\le x^{1/2}$ yields a satisfactory contribution. Since we have taken $D=x^{1/2}$ we may therefore assume in what follows that $x^{1/2}\ll E\ll x^{3/4}$ and $x^{1/2}\ll F\ll x$.

**3. The determinant method.** We begin our analysis of $\mathcal{M}(E,F)$ by using the unique factorization property for $\mathbb{Z}[i]$. This shows that if $e^2f=n^2+1$ then there are integers $x_1,x_2,y_1,y_2$ for which

$$e=x_1^2+x_2^2,\qquad f=y_1^2+y_2^2,\qquad (x_1+ix_2)^2(y_1+iy_2)=n+i.$$

It follows on taking the imaginary part that $2x_1x_2y_1+(x_1^2-x_2^2)y_2=1$. If $|x_1|>|x_2|$ we will swap $x_1$ and $x_2$, and change the sign of $y_2$. Hence we may suppose, without loss of generality, that $|x_1|\le|x_2|$, and hence that $|x_1|\le E^{1/2}$ and $E^{1/2}\ll|x_2|\le E^{1/2}$. We observe that

$$\max\{|2x_1x_2|,|x_1^2-x_2^2|\}\gg x_1^2+x_2^2\gg E.$$

Thus if we write $q_1(x_1,x_2)=2x_1x_2$ or $x_1^2-x_2^2$ as appropriate, and take $q_2$ to be the alternative quadratic form, we may assume that $E\ll|q_1(x_1,x_2)|\ll E$ and $q_2(x_1,x_2)\ll E$. Then, labelling $y_1,y_2$ either as $z_1,z_2$ or as $z_2,z_1$ we will have

$$q_1(x_1,x_2)z_1+q_2(x_1,x_2)z_2=1, \tag{4}$$

whence

$$E|z_1|\ll|q_1(x_1,x_2)z_1|\ll 1+|q_2(x_1,x_2)z_2|\ll 1+E|z_2|.$$

Since we cannot have $z_1=z_2=0$ we deduce that $|z_1|\ll|z_2|$. Then, since $F\ll z_1^2+z_2^2\le F$ we see that $|z_1|\le F^{1/2}$ and $F^{1/2}\ll|z_2|\le F^{1/2}$.

We now deduce from (4) that if $s=x_1/x_2$ and $t=z_1/z_2$ then

$$t=-\frac{q_2(s,1)}{q_1(s,1)}+O(E^{-1}F^{-1/2})=-\frac{q_2(s,1)}{q_1(s,1)}+O(x^{-1}).$$

Thus if we write $\phi(s)=-q_2(s,1)/q_1(s,1)$ then the point $(s,t)$ lies close to the curve $\phi(S)=T$. Our task is therefore to estimate the number of rational points $(s,t)$ with $s,t\ll 1$ lying within $O(x^{-1})$ of the curve $\phi(S)=T$, and for which the "heights" of $s$ and $t$ are at most $E^{1/2}$ and $F^{1/2}$ respectively.

The situation here is similar to that in the author's paper [6]. We shall use a real-variable version of the "determinant method", but there is an important difference, in that the variety given by the equation

$$q_1(x_1,x_2)z_1+q_2(x_1,x_2)z_2=0$$

lies naturally in $\mathbb{P}^1\times\mathbb{P}^1$, rather than in $\mathbb{P}^2$. Indeed this makes our situation correspond exactly to that considered by Huxley [7], [8]. Unfortunately, Huxley's bounds, which were obtained for general plane curves, are not strong enough for our application. In particular, he focuses on the case in which $\phi$ is not a rational function.

Following the method from the author's work [6, §2] we choose an integer parameter $M\in[x^{1/2},x]$ and split the available range for $s$ into $O(M)$ subintervals $I=(s_0,s_0+M^{-1}]$. We then investigate the number of solutions in which $s$ belongs to a particular interval $I$. If we write $s=s_0+u$ we find from Taylor's Theorem that $\phi(s)=\phi(s_0)+u\phi'(s_0)+O(x^{-1})$. Hence if we set $v=t-\phi(s_0)-u\phi'(s_0)$ we will have $s=s_0+u$, $t=\phi(s_0)+u\phi'(s_0)+v$ with $v\ll x^{-1}$. We now label all the solutions corresponding to the interval $I$ as $(s_1,t_1),\dots,(s_J,t_J)$, say. We proceed to choose positive integers $K,L$ and to label the monomials $s^kt^l$ for $k\le K$, $l\le L$ as $m_1(s,t),\dots,m_H(s,t)$, where $H=(K+1)(L+1)$. The determinant method uses the $J\times H$ matrix $\mathcal{M}$, whose $jh$ entry is $m_h(s_j,t_j)$. The aim is to show that the rank of $\mathcal{M}$ is strictly less than $H$. If this can be achieved, one may deduce that there is a non-zero vector $\mathbf{c}$ with

$$\mathcal{M}\mathbf{c}=\mathbf{0}. \tag{5}$$

This vector $\mathbf{c}$ may be constructed out of appropriate subdeterminants of $\mathcal{M}$. Thus its entries will be rational numbers with numerators and denominators of size $\ll_{K,L} x^{H(K+L)}$, since $s_j$ and $t_j$ have numerators and denominators of size $\ll x^{1/2}\ll x$. We now observe that the matrix equation (5) means that there is a polynomial $C(s,t)$, with coefficients given by the vector $\mathbf{c}$, such that $C(s_j,t_j)=0$ for all pairs $(s_j,t_j)$. Multiplying out the common denominator of the coefficients we may assume that $C$ has integer coefficients, of size $\ll_{K,L} x^{H^2(K+L)}$.

This is one of the key stages in the proof. We deduce that all points $(s,t)$ for which $t$ is close to $\phi(s)$, and for which $s$ lies in an appropriate short range $I$, actually lie on the curve $C(s,t)=0$.

We now show that $\mathcal{M}$ does indeed have rank less than $H$, if the parameter $M$ is suitably chosen. For this we select any $H\times H$ subdeterminant, $\Delta$ say, from $\mathcal{M}$, and show that $\Delta=0$. Without loss of generality we may suppose that $\Delta$ comes from the first $H$ rows of $\mathcal{M}$. Since the $j$th row contains rationals with a common denominator of $x_{2,j}^K z_{2,j}^L$ it is clear that

$$\Big(\prod_{j\le H} x_{2,j}^K z_{2,j}^L\Big)\Delta\in\mathbb{Z}.$$

Thus to show that $\Delta=0$ it will suffice to prove that

$$\Delta\ll_{K,L} E^{-KH/2}F^{-LH/2} \tag{6}$$

with a suitably small implied constant.

When we substitute $s=s_0+u$ and $t=\phi(s_0)+u\phi'(s_0)+v$ the monomials $m_j(s,t)$ produce polynomials in $u,v$. Thus $\Delta$ is a generalized van der Monde determinant. If $u_j$ and $v_j$ correspond to $s_j$ and $t_j$ then we have $|u_j|\le M^{-1}$ and $|v_j|\le V^{-1}$ for some $V$ of exact order $x$. An estimate for the size of $\Delta$ is now provided by Lemma 3 from the author's work [6]. If we order all possible monomials $M^{-k}V^{-l}$ according to decreasing size as $1=M_0,M_1,\ldots$ then the lemma shows that

$$\Delta\ll_H \prod_{h=1}^{H} M_h.$$

If $M_H=W^{-1}$ then $M^{-k}V^{-l}\ge M_H$ if and only if

$$k\log M+l\log V\le\log W. \tag{7}$$

The number of such pairs $k,l$ is

$$\frac{(\log W)^2}{2(\log M)(\log V)}+O\Big(\frac{\log W}{\log x}\Big)+O(1),$$

and since this must equal $H$ we deduce that

$$\log W=H^{1/2}\sqrt{2(\log M)(\log V)}+O(\log x). \tag{8}$$

Moreover

$$\begin{aligned}\log\prod_{h=1}^{H}M_h&=-\sum_{k,l}(k\log M+l\log V)\\&=-\frac{(\log W)^3}{3(\log M)(\log V)}+O\Big(\frac{(\log W)^2}{\log x}\Big),\end{aligned}$$

the sum over $k,l$ being subject to (7). It follows from (8) that

$$\log\prod_{h=1}^{H}M_h=-H^{3/2}\frac{2\sqrt{2}}{3}\sqrt{(\log M)(\log V)}+O(H\log x),$$

and hence that

$$\log|\Delta|\le O_H(1)-H^{3/2}\frac{2\sqrt{2}}{3}\sqrt{(\log M)(\log V)}+O(H\log x).$$

This will be sufficient for (6) providing that

$$\frac{K}{2}\log E+\frac{L}{2}\log F\le (KL)^{1/2}\frac{2\sqrt{2}}{3}\sqrt{(\log M)(\log V)}+O_{K,L}(1)+O(\log x).$$

In order to use this optimally we will take $K=[L(\log F)/(\log E)]$. Since our size constraints on $E$ and $F$ imply that $L\ll K\ll L$ it then suffices that

$$L\log F\le L\frac{2\sqrt{2}}{3}\sqrt{(\log M)(\log V)}\,\frac{\sqrt{\log F}}{\sqrt{\log E}}+O_L(1)+O(\log x).$$

Hence if $\delta>0$ is a small positive constant, and

$$\frac{2\sqrt{2}}{3}\sqrt{(\log M)(\log V)}\,\frac{\sqrt{\log F}}{\sqrt{\log E}}\ge(1+\delta)\log F,$$

it will be enough to have $L=L(\delta)$ sufficiently large, and $x\gg_\delta 1$. The condition may be rewritten in the form

$$\log M\ge\frac{9}{8}(1+\delta)^2\frac{(\log E)(\log F)}{\log V}$$

and since $V\gg x$ we may summarize our conclusions as follows.

LEMMA 1. *Let $\eta>0$ be given, and suppose $M\in[x^{1/2},x]$ satisfies*

$$\log M\ge\frac{9}{8}(1+\eta)\frac{(\log E)(\log F)}{\log x}.$$

*Then for any interval $I=[s_0, s_0+M^{-1}]$ there is a corresponding non-zero integer polynomial $C_I(s,t)$ satisfying*

$$C_I(x_1/x_2, z_1/z_2)=0 \tag{9}$$

*for any solution of* (4) *with $x_1/x_2 \in I$. Moreover $C_I$ has total degree $O_\eta(1)$, and coefficients of size $O_\eta(x^\kappa)$ for some constant $\kappa=\kappa(\eta)$.*

**4. Counting solutions of equations.** While the previous section involved the application of a general method, the next stage in the proof requires an *ad hoc* argument, to count points which simultaneously satisfy both (4) and (9). We begin by showing that it suffices to assume that $C_I$ is absolutely irreducible. Let $(s,t)$ be a rational point satisfying $F(s,t)=0$ for some monic factor $F$ of $C_I$ which is not defined over $\mathbb{Q}$. Then $F^\sigma(s,t)=0$ for every conjugate $F^\sigma$. The number of possible points $s,t$ is then $O_\eta(1)$ by Bézout's Theorem. Since $x_1,x_2$ are coprime, and similarly for $z_1,z_2$, we obtain $O_\eta(1)$ solutions this way. Thus we need only consider absolutely irreducible factors $F$ of $C_I$ which are defined over $\mathbb{Z}$. The height of any such factor is again bounded by a power of $x$, by Gelfond's Lemma (see Bombieri and Gubler [1, Lemma 1.6.11] for example). Moreover the number of different factors to consider is $O_\eta(1)$. Thus it suffices to consider the case in which $F(x_1/x_2, z_1/z_2)=0$ for some absolutely irreducible polynomial $F$ satisfying the same conditions as $C_I$.

Our next move is to clear the denominators $x_2$ and $z_2$ so as to replace the equation $F(s,t)=0$ by a bi-homogeneous one

$$F(x_1,x_2;z_1,z_2)=0, \tag{10}$$

say. For a given interval $I$ we will have

$$s_0 < s = \frac{x_1}{x_2} \le s_0 + M^{-1}.$$

It therefore follows that $|x_1 - s_0x_2| \le E^{1/2}M^{-1}$, since $|x_2| \le E^{1/2}$. If we let

$$\Lambda = \{(E^{-1/2}M(x_1-s_0x_2), E^{-1/2}x_2) : (x_1,x_2)\in\mathbb{Z}^2\}$$

then $\Lambda$ is a lattice of determinant $E^{-1}M$, and we are interested in points $(\alpha_1,\alpha_2)\in\Lambda$ falling in the square

$$S=\{(\alpha_1,\alpha_2) : \max(|\alpha_1|,|\alpha_2|)\le 1\}.$$

Let $\mathbf{g}^{(1)}$ be the shortest non-zero vector in the lattice and $\mathbf{g}^{(2)}$ the shortest vector not parallel to $\mathbf{g}^{(1)}$. These vectors will form a basis for $\Lambda$. Moreover we have $\lambda_1\mathbf{g}^{(1)}+\lambda_2\mathbf{g}^{(2)}\in S$ only when $|\lambda_1| \ll |\mathbf{g}^{(1)}|^{-1}$ and $|\lambda_2| \ll |\mathbf{g}^{(2)}|^{-1}$. These constraints may be written in the form $|\lambda_i| \le L_i$, for appropriate bounds $L_1, L_2$. Since $|\mathbf{g}^{(2)}| \ge |\mathbf{g}^{(1)}|$ and $|\mathbf{g}^{(1)}|\cdot|\mathbf{g}^{(2)}| \ll \det(\Lambda)=E^{-1}M$ we will have $L_1 \gg L_2$ and $L_1 L_2 \gg EM^{-1}$. We now write

$$\mathbf{h}^{(i)} = E^{1/2}(M^{-1}g_1^{(i)} + s_0 g_2^{(i)}, g_2^{(i)})$$

for $i = 1, 2$. These vectors will then be a basis for $\mathbb{Z}^2$, and if $\mathbf{x} = \lambda_1 \mathbf{h}^{(1)} + \lambda_2 \mathbf{h}^{(2)}$ is in the region given by $|x_1 - s_0 x_2| \le E^{1/2}M^{-1}$ and $|x_2| \le E^{1/2}$ then we will have $|\lambda_i| \le L_i$ for $i = 1, 2$. This allows us to make a change of basis, replacing $(x_1, x_2)$ by $(\lambda_1, \lambda_2)$ so that our constraints on $x_1, x_2$ are replaced by the conditions $|\lambda_i| \le L_i$.

We may argue in exactly the same way for $z_1, z_2$ using the fact that

$$t = z_1/z_2 = \phi(s_0) + u\phi'(s_0) + O(x^{-1}) = \phi(s_0) + O(M^{-1}).$$

This allows us to replace the variables $z_1, z_2$ by $\tau_1, \tau_2$ subject to $|\tau_i| \le T_i$. Here $T_1 \gg T_2$ and $T_1 T_2 \ll FM^{-1}$. These substitutions convert (4) into a new equation

$$G_0(\lambda_1, \lambda_2; \tau_1, \tau_2) = 1, \tag{11}$$

say, where $G_0$ is bi-homogeneous of degree $(2, 1)$. Similarly they will turn (10) into an equation of the shape

$$G_1(\lambda_1, \lambda_2; \tau_1, \tau_2) = 0 \tag{12}$$

where $G_1$ is bi-homogeneous of degree $(a, b)$, say. Of course it is apparent from (11) that the vectors $(\lambda_1, \lambda_2)$ and $(\tau_1, \tau_2)$ will be primitive.

When $\min(a, b) \ge 2$ we can get a satisfactory bound from the following general result, which will be proved later, in §6.

Lemma 2. *Let $G(x_1, x_2; y_1, y_2) \in \mathbb{Z}[x_1, x_2, y_1, y_2]$ be an absolutely irreducible bi-homogeneous polynomial of degree $(a, b)$ with $a, b \ge 1$. Let $\varepsilon > 0$ be given. Then for any $X \ge 1$ there are $O_{a,b,\varepsilon}(X^{2/b+\varepsilon}\|G\|^{\varepsilon})$ points $(x_1, x_2, y_1, y_2) \in \mathbb{Z}^4$ satisfying the conditions*

$$\text{g.c.d.}(x_1, x_2) = 1, \quad \text{g.c.d.}(y_1, y_2) = 1, \quad G(x_1, x_2; y_1, y_2) = 0, \quad \max_i |x_i| \le X.$$

Notice here that there is no size constraint on $y_1$ or $y_2$.

When $a \ge 2$ the lemma shows that (12) has $O_\eta(T_1^{1+\eta}x^\eta)$ solutions $\lambda_1, \lambda_2, \tau_1, \tau_2$. Each of these corresponds to at most one solution of (4), and therefore contributes $O(1)$ to $\mathcal{M}(E, F)$. Similarly, if $b \ge 2$ then there are $O_\eta(L_1^{1+\eta}x^\eta)$ solutions.

We next dispose of the case in which $a$ or $b$ is zero. For example, if $a = 0$ then (12) specifies a finite number $O_\eta(1)$ of pairs $\tau_1, \tau_2$, and for each of these there is a corresponding pair $(z_1, z_2)$, producing the value of $f = z_1^2 + z_2^2$. Each such $f$ contributes $O(\log x)$ to $\mathcal{M}(E, F)$ by Estermann's bound (3). Thus the interval $I$ contributes $O_\eta(\log x)$ when $a = 0$. Similarly if $b = 0$ there are $O_\eta(1)$ corresponding values for $e$. As in (2) each such value $e$ contributes

$\ll \rho(e)(xe^{-2}+1)$ to $\mathcal{M}(E,F)$. This is also satisfactory, since

$$e \geq E \gg D = x^{1/2}$$

and $\rho(e) \ll_\eta x^\eta$. Thus we have $O_\eta(x^\eta)$ solutions corresponding to $I$ when $\min(a,b)=0$.

When $a=1$, equation (12) can be written

$$\lambda_1 G_{11}(\tau_1,\tau_2) + \lambda_2 G_{12}(\tau_1,\tau_2) = 0.$$

Thus $\lambda_1 = q^{-1}G_{12}(\tau_1,\tau_2)$, $\lambda_2 = -q^{-1}G_{11}(\tau_1,\tau_2)$, where $q$ divides $G_{11}(\tau_1,\tau_2)$ and $G_{12}(\tau_1,\tau_2)$. Since $\tau_1$ and $\tau_2$ are coprime it follows that $q$ divides the resolvent $R$ of $G_{11}$ and $G_{12}$. This resolvent is non-zero since $G_1$ is irreducible. Moreover it is bounded by a power of $x$, whence there are $O_\eta(x^\eta)$ possible choices for $q$. (The reader should recall at this point that the forms $G_{11}$ and $G_{12}$ are determined, up to $O_\eta(1)$ possibilities, by the interval $I$.) For each available choice of $q$ we substitute our values for $\lambda_1, \lambda_2$ into (11) to obtain a Thue equation $G_3(\tau_1,\tau_2) = q^2$. Unfortunately we cannot use the full force of known results on such equations, since it is possible for $G_3$ to be a power of a linear form. Nonetheless there can be at most $O(T_1)$ possible pairs $\tau_1,\tau_2$. It follows that we have at most $O_\eta(x^\eta T_1)$ solutions in total. The case $b=1$ is entirely analogous, leading to a bound $O_\eta(x^\eta L_1)$.

In summary we have a bound $O_\eta(T_1^{1+\eta}x^\eta)$ on the number of solutions, in each of the cases $a \geq 2$, or $a=0$, or $a=1$. Similarly we have an estimate $O_\eta(L_1^{1+\eta}x^\eta)$ whatever the value of $b$. We therefore conclude as follows.

Lemma 3. *For any $\eta > 0$ the contribution to $\mathcal{M}(E,F)$ corresponding to a single interval $I$ is $O_\eta(x^\eta \min(L_1^{1+\eta}, T_1^{1+\eta}))$.*

**5. Completion of the proof.** Having fixed $M$ as in Lemma 1 we must now sum up $\min(L_1,T_1)$ for the various intervals $I$. In the notation of the previous section, if $(x_1,x_2)$ corresponds to $\mathbf{g}^{(1)}$ then $L_1(x_1 - s_0x_2) \ll M^{-1}\sqrt{E}$ and $L_1x_2 \ll \sqrt{E}$. If $L_1 \gg \sqrt{E}$ we see that $x_2=0$, and then $x_1=0$, which is impossible. The intervals $I = (s_0, s_0+M^{-1}]$ will be produced by taking $s_0 = x_3M^{-1}$ for integers $x_3 \ll M$. Thus the number of intervals for which $L \leq L_1 \leq 2L$ is at most the number of triples $(x_1,x_2,x_3) \in \mathbb{Z}^3$ with g.c.d.$(x_1,x_2)=1$, for which

$$x_2x_3 = Mx_1 + O(L^{-1}\sqrt{E}), \qquad x_2 \ll L^{-1}\sqrt{E}, \qquad x_3 \ll M.$$

We now recall that $L_1 \gg L_2$ and that $L_1L_2 \gg EM^{-1}$. Thus $L \gg E^{1/2}M^{-1/2}$. Moreover, as noted above, we have $L \ll E^{1/2}$. In particular, if $M$ is large enough we can have $x_2x_3 = 0$ only when $x_1 = 0$. Since $x_1$ and $x_2$ are coprime this case can arise only when $x_2 = \pm 1$ and $x_3 = 0$. When $x_2x_3 \neq 0$ the conditions on $x_2$ and $x_3$ imply that $x_1 \ll L^{-1}\sqrt{E}$, and a divisor function estimate then shows that there are $O_\eta(x^\eta L^{-1}\sqrt{E})$ pairs $x_2,x_3$ for each value of $x_1$. We conclude that there are $O_\eta(x^\eta L^{-2}E)$ intervals $I$ for which $L_1$ is of order $L$. Since each interval makes a contribution $\ll_\eta x^\eta L_1^{1+\eta}$, by Lemma 3, we get a total $\ll_\eta x^\eta L^{-1+\eta}E \ll x^{2\eta}L^{-1}E$, since $L \ll E^{1/2} \ll x$. By dyadic subdivision for $L \gg E^{1/2}M^{-1/2}$ we find that $\mathcal{M}(E,F) \ll_\eta x^{2\eta}(EM)^{1/2}$.

We can prove a precisely analogous estimate $\mathcal{M}(E,F) \ll_\eta x^{2\eta}(FM)^{1/2}$ by considering the number of intervals $J = (\phi(s_0), \phi(s_0) + O(M^{-1})]$ which produce a value $T_1$ in a given dyadic range $(T, 2T]$. Here we use the fact that $J \subseteq (t_3M^{-1}, t_3M^{-1} + O(M^{-1})]$ for some integer $t_3$. We also need to remark that each value of $t_3$ occurs $O(1)$ times, since $|\phi'(s)| \gg 1$ for the values of $s$ under consideration. With these observations the argument then goes through just as before. We may therefore conclude that

$$\mathcal{M}(E,F) \ll_\eta x^{2\eta}(\min(E,F)M)^{1/2}.$$

It remains to use this result with the value for $M$ coming from Lemma 1. It is convenient to write $E = x^\psi$, so that $F = x^{2-2\psi+O(1/\log x)}$. In view of our remarks at the end of §2 we have (essentially) $1/2 \le \psi \le 3/4$. We may then employ a value $M$ with

$$\frac{\log M}{\log x} = (1+\eta)\max\left\{\frac{9\psi(1-\psi)}{4}, \frac{1}{2}\right\} + O((\log x)^{-1}).$$

This value will automatically satisfy $M \in [x^{1/2}, x]$ if $\eta$ is small enough. It follows that

$$\frac{\log \mathcal{M}(E,F)}{\log x} \le 2\eta + \frac{1}{2}\min(\psi, 2-2\psi) + (1+\eta)\max\left\{\frac{9\psi(1-\psi)}{8}, \frac{1}{4}\right\} + O_\eta((\log x)^{-1}).$$

However, since

$$\frac{1}{2}\min(\psi, 2-2\psi) + \max\left\{\frac{9\psi(1-\psi)}{8}, \frac{1}{4}\right\} \le \frac{7}{12}$$

for the relevant range of $\psi$, we deduce that $\mathcal{M}(E,F) \ll_\eta x^{3\eta+7/12}$, and our theorem then follows.

**6. Lemma 2.** Lemma 2 is closely related to two results of Broberg. In [2, Theorem 1] Broberg establishes a general result about finite covers of $\mathbb{P}^1$ which, when translated into our notation, would provide an estimate $O_{G,a,b,\varepsilon}(X^{2/b+\varepsilon})$ of the desired order, but without any explicit dependence on $G$. This explicit dependence can be deduced from a second result of Broberg [3], but this has not been formally published. We therefore give a brief sketch of a direct argument independent of these two papers. This uses the determinant method, for more details of which the reader should consult [5, §3].

We will need a crude bound on the size of $\mathbf{y}$. Let

$$G(\mathbf{x};\mathbf{y}) = G_0(\mathbf{x})y_1^b + \cdots + G_b(\mathbf{x})y_2^b.$$

The form $G_0$ cannot vanish identically since $G$ is irreducible. Thus there are $O_a(1)$ primitive integer vectors $\mathbf{x}$ for which $G_0(\mathbf{x}) = 0$. It is not possible for all the forms $G_i(\mathbf{x})$ to vanish simultaneously for a vector $\mathbf{x} \neq \mathbf{0}$, since $G$ is irreducible. Thus, with $O_{a,b}(1)$ exceptions, any solution of $G(\mathbf{x};\mathbf{y}) = 0$ has $y_2 \mid G_0(\mathbf{x})$, with $G_0(\mathbf{x}) \neq 0$. We may therefore assume that $|y_2| \ll X^a\|G\|$, and similarly for $y_1$. It will be convenient to write these bounds in the form $|y_1|, |y_2| \le Y$, with $Y \ll X^a\|G\|$.

Our overall plan now is to apply the $p$-adic determinant method. By making an invertible integral linear substitution on $\mathbf{x}$ we may assume that $G_0(1,0) \neq 0$. Indeed we can choose the coefficients of the substitution to be bounded in terms of $a$ alone, so that we may still assume that $|\mathbf{x}| \ll_a X$. Suppose we have a parameter $P \gg_{a,b} \log X\|G\|$. Then for any solution $\mathbf{x}, \mathbf{y}$ of $G(\mathbf{x};\mathbf{y}) = 0$ with $|\mathbf{x}| \ll_a X$, $|\mathbf{y}| \ll Y$, either we have

$$x_2 y_2 \frac{\partial G(\mathbf{x};\mathbf{y})}{\partial y_1} = 0$$

or there is a prime $p \in (P, 2P]$ not dividing $x_2 y_2 (\partial G/\partial y_1)$. The first case immediately gives us an auxiliary bi-homogeneous form $H(\mathbf{x};\mathbf{y})$ not divisible by $G$, at which our solution also vanishes. In the alternative case the point $(x_1/x_2, y_1/y_2)$ lies above a smooth $\mathbb{F}_p$-point on the curve $G(s,1;t,1) = 0$. We can then expand $y_1/y_2$ as a $p$-adic power series in $x_1/x_2$, as in Lemma 5 of the author's paper [5]. We then consider the matrix of bi-homogeneous monomials in $\mathbf{x}$ and $\mathbf{y}$ of degree $(H, b-1)$. There are $k := (H+1)b$ such monomials. The corresponding $k \times k$ determinant then has archimedean size $\ll_{a,b,H} (X^H Y^{b-1})^k$. Moreover it will be divisible by $p^{k(k-1)/2}$. The argument of [5, §3] then produces an auxiliary form $H(\mathbf{x};\mathbf{y})$ providing that

$$p \gg_{a,b,H} X^{2H/(k-1)} Y^{2(b-1)/(k-1)}.$$

We now recall that $Y \ll X^a\|G\|$. Thus on choosing $H$ sufficiently large we see that it suffices to have $p \gg_{a,b,\varepsilon} (X\|G\|)^{\varepsilon} X^{2/b}$. In addition to the form $x_2 y_2 \partial G/\partial y_1$ that we have already mentioned we now obtain one further form $H(\mathbf{x};\mathbf{y})$ for each $\mathbb{F}_p$-point on the curve $G(s,1;t,1) = 0$. We thus conclude that every solution to $G(\mathbf{x};\mathbf{y}) = 0$ with $\max|x_i| \le X$ satisfies one of the $O_{a,b,\varepsilon}((X\|G\|)^{\varepsilon} X^{2/b})$ auxiliary conditions $H(\mathbf{x};\mathbf{y}) = 0$. Here $H$ is a bi-linear form coprime to $G$, with degrees bounded in terms of $a, b$ and $\varepsilon$. For each such form, there are $O_{a,b,\varepsilon}(1)$ common solutions to $G(s,1;t,1) = H(s,1;t,1) = 0$ by Bézout's Theorem, and $s, t$ determine $\mathbf{x}, \mathbf{y}$ since these vectors are primitive. This suffices for the lemma.

**7. Further improvements.** It is possible to reduce slightly the exponent 7/12 occurring in the theorem. Since the improvement is very small we content ourselves with a very brief sketch of the argument.

The first step is to repeat the analysis of §3 taking $K = L = 1$ and obtaining a bi-linear form $F$ in (10), providing that $M \in [x^{1/2}, x]$ satisfies $M \geq (E^{1/3}F^{1/2})^{1+\delta}$. Note here that in fact

$$x^{1/2} \leq (E^{1/3}F^{1/2})^{1+\delta} \leq x$$

for large enough $x$ and small enough $\delta$, as $x^2 \ll E^2F \ll x^2$ and $E, F \gg x^{1/2}$.

When $F$ is bi-linear the Thue equation referred to in §4 will have degree 3, and will produce $O_\eta(x^\eta)$ solutions for each interval $I$, except when $G_3$ is proportional to a cube. In this case the corresponding solutions of

$$2x_1x_2y_1 + (x_1^2 - x_2^2)y_2 = 1 \tag{13}$$

lie on a line

$$(x_1, x_2, y_1, y_2) = (x_1^{(0)}, x_2^{(0)}, y_1^{(0)}, y_2^{(0)}) + \lambda(\mu_1, \mu_2, \nu_1, \nu_2)$$

contained in the variety (13).

We now write $\mathcal{M}_0(E, F)$ for the number of quadruples $(x_1, x_2, y_1, y_2)$ satisfying (13), for which

$$E/2 < x_1^2 + x_2^2 \leq E, \qquad F/2 < y_1^2 + y_2^2 \leq F$$

but which do not lie on a line in the variety (13). We may then deduce that

$$\mathcal{M}_0(E, F) \ll_\eta x^{2\eta}E^{1/3}F^{1/2} \ll_\eta x^{2\eta+2/3-\psi/6},$$

where $E = x^\psi$ as before. Alternatively we can use our previous argument to show that

$$\mathcal{M}_0(E, F) \leq \mathcal{M}(E, F) \ll_\eta x^{3\eta+\min(\psi,2-2\psi)/2+9\psi(1-\psi)/8}.$$

These suffice to show that

$$\mathcal{M}_0(E, F) \ll_\eta x^{3\eta+46/81},$$

the critical value of $\psi$ being 16/27.

It then remains to consider the form taken by lines lying in the surface (13). The lines which contain more than one integral point may be described explicitly, and one is then able to show that they contribute $O_\eta(x^{\eta+1/2})$ to $\mathcal{M}(E, F)$.

In this way one may improve the exponent in the theorem to 46/81.

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