

LATTICE POINTS ON CIRCLES, SQUARES IN ARITHMETIC PROGRESSIONS AND SUMSETS OF SQUARES

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ABSTRACT. We discuss the relationship between various additive problems concerning squares.

1. SQUARES IN ARITHMETIC PROGRESSION

Let $\sigma(k)$ denote the maximum of the number of squares in $a + b, \dots, a + kb$ as we vary over positive integers a and b . Erdős conjectured that $\sigma(k) = o(k)$ which Szemerédi [30] elegantly proved as follows: If there are more than δk squares amongst the integers $a + b, \dots, a + kb$ (where k is sufficiently large) then there exists four indices $1 \leq i_1 < i_2 < i_3 < i_4 \leq k$ in arithmetic progression such that each $a + i_j b$ is a square, by Szemerédi's theorem. But then the $a + i_j b$ are four squares in arithmetic progression, contradicting a result of Fermat. This result can be extended to any given field L which is a finite extension of the rational numbers: From Faltings' theorem we know that there are only finitely many six term arithmetic progressions of squares in L , so from Szemerédi's theorem we again deduce that there are $o_L(k)$ squares of elements of L in any k term arithmetic progression of numbers in L . (Xavier Xarles [31] recently proved that there are never six squares in arithmetic progression in $\mathbb{Z}[\sqrt{d}]$ for any d .)

In his seminal paper *Trigonometric series with gaps* [27] Rudin stated the following conjecture:

Conjecture 1. $\sigma(k) = O(k^{1/2})$.

It may be that the most squares appear in the arithmetic progression $-1 + 24i$, $1 \leq i \leq k$ once $k \geq 8$ yielding that $\sigma(k) = \sqrt{\frac{8}{3}k} + O(1)$. Conjecture 1 evidently implies the following slightly weaker version:

Conjecture 2. For any $\varepsilon > 0$ we have $\sigma(k) = O(k^{1/2+\varepsilon})$.

Bombieri, Granville and Pintz [4] proved that $\sigma(k) = O(k^{2/3+o(1)})$, and recently Bombieri and Zannier [5] have proved that $\sigma(k) = O(k^{3/5+o(1)})$.

2. RUDIN'S APPROACH

Let $e(\theta) := e^{2i\pi\theta}$ throughout. The following well-known conjecture was discussed by Rudin (see the end of section 4.6 in [27]):

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Conjecture 3. *For any $2 \leq p < 4$ there exists a constant C_p such that, for any trigonometric polynomial $f(\theta) = \sum_k a_k e(k^2\theta)$ we have*

$$(2.1) \quad \|f\|_p \leq C_p \|f\|_2.$$

Here, as usual, we define $\|f\|_p^p := \int_0^1 |f(t)|^p dt$ for a trigonometric polynomial f . Conjecture 3 says that the set of squares is a $\Lambda(p)$ -set for any $2 \leq p < 4$, where E is a $\Lambda(p)$ -set if there exists a constant C_p such that (2.1) holds for any f of the form $f(\theta) = \sum_{n_k \in E} a_k e(n_k \theta)$ (a so-called E -polynomial). By Hölder's inequality we have, for $r < s < t$,

$$(2.2) \quad \|f\|_s^{s(t-r)} \leq \|f\|_r^{r(t-s)} \|f\|_t^{t(s-r)};$$

taking $r = 2$ we see that if E is a $\Lambda(t)$ -set then it is a $\Lambda(s)$ -set for all $s \leq t$.

Let $r(n)$ denote the number of representations of n as the sum of two squares (of positive integers). Taking $f(\theta) = \sum_{1 \leq k \leq x} e(k^2\theta)$, we deduce that $\|f\|_2^2 = x$, whereas $\|f\|_4^4 = \sum_n \#\{1 \leq k, \ell \leq x : n = k^2 + \ell^2\}^2 \geq \sum_{n \leq x^2} r(n)^2 \asymp x^2 \log x$; so we see that (2.1) does not hold in general for $p = 4$.

Conjecture 3 has not been proved for any $p > 2$, though Rudin [27] has proved the following theorem.

Theorem 1. *If E is a $\Lambda(p)$ -set, then any arithmetic progression of N terms contains $\ll N^{2/p}$ elements of E . In particular, if Conjecture 3 holds for p then $\sigma(k) = O(k^{2/p})$.*

Proof: We use Fejér's kernel $\kappa_N(\theta) := \sum_{|j| \leq N} (1 - \frac{|j|}{N}) e(j\theta)$. Note that $\|\kappa_N\|_1 = 1$ and $\|\kappa_N\|_2^2 = \sum_{|j| \leq N} (1 - \frac{|j|}{N})^2 \ll N$ so, by (2.2) with $r = 1 < s = q < t = 2$ we have $\|\kappa_N\|_q^q \ll 1^{2-q} N^{q-1}$ so that $\|\kappa_N\|_q \ll N^{1/p}$ where $\frac{1}{q} + \frac{1}{p} = 1$.

Suppose that $n_1, n_2, \dots, n_\sigma$ are the elements of E which lie in the arithmetic progression $a + ib, 1 \leq i \leq N$. If $n_\ell = a + ib$ for some $i, 1 \leq i \leq N$ then $n_\ell = a + mb + jb$ where $m = [(N+1)/2]$ and $|j| \leq N/2$; and so $1 - \frac{|j|}{N} \geq \frac{1}{2}$. Therefore, for $g(\theta) := \sum_{1 \leq \ell \leq \sigma} e(n_\ell \theta)$, we have

$$\int_0^1 g(-\theta) e((a + bm)\theta) \kappa_N(b\theta) d\theta \geq \frac{\sigma}{2}.$$

On the other hand, we have $\|g\|_p \leq C_p \|g\|_2 \ll \sqrt{\sigma}$ since E is a $\Lambda(p)$ -set and g is an E -polynomial. Therefore, by Hölder's inequality,

$$(2.3) \quad \left| \int_0^1 g(-\theta) e((a + bm)\theta) \kappa_N(b\theta) d\theta \right| \leq \|g\|_p \|\kappa_N\|_q \ll \sqrt{\sigma} N^{1/p}$$

and the result follows by combining the last two displayed equations.

It is known that Conjecture 3 is true for polynomials $f(\theta) = \sum_{k \leq N} e(k^2\theta)$ and Antonio Córdoba [18] proved that Conjecture 3 also holds for polynomials $f(\theta) = \sum_{k \leq N} a_k e(k^2\theta)$ when the coefficients a_k are positive real numbers and non-increasing.

3. SUMSETS OF SQUARES

For a given finite set of integers E let $f_E(\theta) = \sum_{k \in E} e(k\theta)$. Mei-Chu Chang [11] conjectured that for any $\varepsilon > 0$ we have

$$\|f_E\|_4 \ll_\varepsilon \|f_E\|_2^{1+\varepsilon}$$

for any finite set of squares E . As $\|f_E\|_4^4 = \sum_n r_{E+E}^2(n)$ where $r_{E+E}(n)$ is the number of representations of n as a sum of two elements of E , her conjecture is equivalent to:

Conjecture 4 (Mei-Chu Chang). *For any $\varepsilon > 0$ we have that*

$$(3.1) \quad \|f_E\|_4^4 = \sum_n r_{E+E}^2(n) \ll |E|^{2+\varepsilon} = \|f_E\|_2^{4+2\varepsilon}$$

for any finite set E of squares.

We saw above that $\sum_n r_{E+E}^2(n) \gg |E|^2 \log |E|$ in the special case $E = \{1^2, \dots, k^2\}$, so conjecture 4 is sharp, in the sense one cannot entirely remove the ε .

Trivially we have

$$\|f_E\|_4^4 = \sum_n r_{E+E}^2(n) \leq \max r_{E+E}(n) \sum_n r_{E+E}(n) \leq |E| \cdot |E|^2 = |E|^3$$

for any set E ; it is surprisingly difficult to improve this estimate when E is a set of squares. The best such result is due to Mei-Chu Chang [11] who proved that

$$\sum_n r_{E+E}^2(n) \ll |E|^3 / \log^{1/12} |E|$$

for any set E of squares. Assuming a major conjecture of arithmetic geometry we can improve Chang's result, in a proof reminiscent of that in [4]:¹

Theorem 2. *Assume the Bombieri-Lang conjecture. Then, for any set E of squares, and any set of integers A , we have*

$$\sum_n r_{E+A}^2(n) \ll |A|^2 |E|^{3/4} + |A| |E|.$$

In particular

$$\sum_n r_{E+E}^2(n) \ll |E|^{11/4}.$$

Proof: One consequence of [10] is that there exists an integer B , such that if the Bombieri-Lang conjecture is true then for any polynomial $f(x) \in \mathbb{Z}[x]$ of degree five or six which does not have repeated roots, there are no more than B rational numbers m for which $f(m)$ is a square. For any given set of five elements $a_1, \dots, a_5 \in A$ consider all integers n for which there exist $b_1, \dots, b_5 \in E$ with $n = a_1 + b_1^2 = \dots = a_5 + b_5^2$. Evidently $f(n) = (b_1 \dots b_5)^2$ where $f(x) = \prod_{i=1}^5 (x - a_i)$, and so there cannot be more than B such integers n . Therefore,

$$\begin{aligned} \sum_n \binom{r_{E+A}(n)}{5} &= \sum_n \#\{a_1, \dots, a_5 \in E : \exists b_1^2, \dots, b_5^2 \in E, \text{ with } n = a_i^2 + b_i^2, i = 1, \dots, 5\} \\ &= \sum_{a_1, \dots, a_5 \in A} \#\{n : \exists b_1^2, \dots, b_5^2 \in E, \text{ with } n = a_i + b_i^2, i = 1, \dots, 5\} \leq B \binom{|A|}{5}. \end{aligned}$$

We have $\sum_n r_{E+A}(n) = |E| |A|$; and so $\sum_n r_{E+A}(n)^5 \ll \sum_n \binom{r_{E+A}(n)}{5} + \sum_n r_{E+A}(n) \ll |A|^5 + |A| |E| \ll |A|^5$. Therefore, by Holder's inequality, we have

$$\sum_n r_{E+A}^2(n) \leq \left(\sum_n r_{E+A}(n) \right)^{3/4} \left(\sum_n r_{E+A}^5(n) \right)^{1/4} \ll |A|^2 |E|^{3/4} + |A| |E|.$$

¹The final versions of Theorems 2 and 3 were inspired by email correspondence with Jozsef Solymosi.

Theorem 3. *Assume the Bombieri-Lang conjecture. Then, for any set E of squares, and any set of integers A , we have*

$$|E + A| \gg \begin{cases} |E||A| & \text{if } |A| \ll |E|^{1/4} \\ |E|^{5/4} & \text{if } |E|^{1/4} \ll |A| \ll |E| \\ |E||A|^{1/4} & \text{if } |E| \ll |A| \ll |E|^{4/3} \\ |A| & \text{if } |E|^{4/3} \ll |A|. \end{cases}$$

Proof:

$$|E|^2|A|^2 = \left(\sum r_{E+A}(n) \right)^2 \leq |E + A| \sum r_{E+A}^2(n) \ll |E + A|(|A|^2|E|^{3/4} + |A||E|).$$

It proves the inequality for $|A| \ll |E|$. For $|A| \gg |E|$ we use a different argument.

There are $|A| \binom{|E|}{4}$ 4-tuples $(a + b_1, \dots, a + b_4)$ with $b_1 < \dots < b_4$ and each $b_i \in E$, $a \in A$. Moreover there are $\binom{|E+A|}{4}$ possible 4-tuples. Now any such 4-tuple (x_1, \dots, x_4) give rise to the integral point $(b_1^{1/2}, (b_2 b_3 b_4)^{1/2})$ on $Y^2 = (X^2 + x_2 - x_1)(X^2 + x_3 - x_1)(X^2 + x_4 - x_1)$. By Bombieri-Lang there are $\ll 1$ such points and so $|A| \binom{|E|}{4} \ll \binom{|E+A|}{4}$ which implies $|E + A| \gg |E||A|^{1/4}$ and the theorem follows since the obvious estimate $|E + A| \geq |A|$ always is true.

It should be noted that corollary above is sharp when $|A| \ll |E|^{1/4}$. The following conjecture deals with the most interesting case, $A = E$.

Conjecture 5 (Ruzsa). *If E is a finite set on squares then, for every $\varepsilon > 0$ we have*

$$|E + E| \gg |E|^{2-\varepsilon}.$$

Theorem 4. *Conjecture 4 implies Conjecture 5 with the same ε .*

Proof: By the Cauchy-Schwarz inequality we have

$$|E|^4 = \left(\sum_n r_{E+E}(n) \right)^2 \leq |E + E| \cdot \sum_n r_{E+E}^2(n)$$

and the result follows.

Theorem 5. *Conjecture 5 implies Conjecture 2 with $\varepsilon_{\text{conj } 2} = \varepsilon_{\text{conj } 5} / (4 - 2\varepsilon_{\text{conj } 5})$.*

Proof: If E is a set of squares which is a subset of an arithmetic progression P of length k then $E + E \subset P + P$. From conjecture 5 we deduce that

$$|E|^{2-\varepsilon} \ll |E + E| \leq |P + P| = 2k - 1$$

and the result follows.

In particular, theorems 2, 4 and 5 show that the Bombieri-Lang conjecture implies $\sigma(k) \ll k^{4/5}$, which is easily obtained by applying directly the Bombieri-Lang conjecture to our arithmetic progression. To do better than this suppose that there are $\sigma_{r,s}$ squares amongst $a + ib, 1 \leq i \leq k$ which are $\equiv r \pmod{s}$; that is the squares amongst $a + rb + jsb, 0 \leq j \leq [k/s]$. This gives rise to $\binom{\sigma_{r,s}}{6}$ rational points on the set of curves

$y^2 = x \prod_{j=1}^5 (x + n_j)$ for $0 \leq n_1 < n_2 < \dots < n_5 \leq [k/s]$. Summing over all $r \pmod{s}$ and all $s > \sigma/10$ we get

$$\frac{k^5}{\sigma^5} \gg \binom{10k/\sigma}{5} \gg \sum_{s > \sigma/10} \sum_{r \pmod{s}} \binom{\sigma_{r,s}}{6} \gg \sum_{s > \sigma/10} s \binom{[\sigma/s]}{6} \gg \sigma^2$$

and we obtain $\sigma(k) \ll k^{5/7}$. Anyway this upper bound was improved unconditionally in [4] and [5].

Email correspondence with Solymosi inspired the following result:

Theorem 6. *Assume the Bombieri-Lang conjecture. There exists a constant $c > 0$ such that for any finite set E of squares we have $r_{E+E}(n) \leq c\sqrt{|E+E|}$ for all integers n .*

Proof: Suppose, on the contrary, that $r_{E+E}(n) > c\sqrt{|E+E|}$ for some integer n . Let $A := \{a : a + a' = n, a, a' \in E\}$, so that

$$\max_m r_{A+A}(m) \geq \frac{1}{|A+A|} \sum_m r_{A+A}(m) = \frac{|A|^2}{|A+A|} = \frac{r_{E+E}(n)^2}{|A+A|} \geq \frac{c^2|E+E|}{|E+E|} = c^2.$$

Now for each a for which $m - a \in A \subset E$, we have $m - a, n - a, n - m + a \in E$ and therefore an integral point on the curve $y^2 = (x^2 - m)(x^2 - n)(x^2 + n - m)$. If c^2 is greater then the constant B involved in the Bombieri-Lang conjecture we get a contradiction.

Corollary 1. *Assume the Bombieri-Lang conjecture. For any finite set E of squares we have $|E+E| \gg |E|^{4/3}$.*

Proof: We deduce, from the Theorem, that

$$|E|^2 = \sum_n r_{E+E}(n) \leq |E+E| \max_n r_{E+E}(n) \leq c|E+E|^{3/2},$$

and the result follows.

An *affine cube* of dimension d in \mathbb{Z} is a set of integers $\{b_0 + \sum_{i \in I} b_i : I \subset \{1, \dots, d\}\}$ for non-zero integers b_0, \dots, b_d . In [28], Solymosi states

Conjecture 6 (Solymosi). *There exists an integer $d > 0$ such that there is no affine cube of dimension d of distinct squares.*

This was asked earlier as a question by Brown, Erdős and Freedman in [9], and Hegyvári and Sárközy [21] have proved that an affine cube of squares, all $\leq n$, has dimension $\leq 48(\log n)^{1/3}$.

This conjecture follows from the Bombieri-Lang conjecture for if there were an affine cube of dimension d then for any $x^2 \in \{b_0 + \sum_{i \in I} b_i : I \subset \{3, \dots, d\}\}$ we have that $x^2 + b_1, x^2 + b_2, x^2 + b_1 + b_2$ are also squares, in which case there are $\geq 2^{d-2}$ integers x for which $f(x) = (x^2 + b_1)(x^2 + b_2)(x^2 + b_1 + b_2)$ is also square; and so $2^{d-2} \leq B$, as in the proof of theorem 2.

In [28], Solymosi gives a beautiful proof that for any set of real numbers A , if $|A+A| \ll_d |A|^{1+\frac{1}{2^{d-1}-1}}$ then A contains many affine cubes of dimension d . Therefore we deduce a weak version of Ruzsa's conjecture from Solymosi's conjecture:

Theorem 7. *Conjecture 6 implies that there exists $\delta > 0$ for which $|A + A| \gg |A|^{1+\delta}$, for any set A of squares.*

The Erdős-Szemerédi conjecture states that for any set of integers A we have

$$|A + A| + |A \diamond A| \gg_\varepsilon |A|^{2-\varepsilon}.$$

In fact they gave a stronger version, reminiscent of the Balog-Szemerédi-Gowers theorem:

Conjecture 7 (Erdős-Szemerédi). *If A is a finite set on integers and $G \subset A \times A$ with $|G| \gg |A|^{1+\varepsilon/2}$ then*

$$(3.2) \quad |\{a + b : (a, b) \in G\}| + |\{ab : (a, b) \in G\}| \gg_\varepsilon |G|^{1-\varepsilon}.$$

Mei-Chu Chang [11] proved that a little more than Conjecture 7 implies Conjecture 4:

Theorem 8. *If (3.2) holds whenever $|G| \geq \frac{1}{2}|A|$ then Conjecture 4 holds.*

Proof: Let B be a set of k non-negative integers and $E = \{b^2 : b \in B\}$. Define $G_M := \{(a_+, a_-) : \exists b, b' \in B \text{ with } a_+ = b + b', a_- = b - b', \text{ and } b^2 - b'^2 \in M\}$ where $M \subset E - E$; and so $A_M := \{a_+, a_- : (a_+, a_-) \in G_M\} \subset (B + B) \cup (B - B)$. Therefore $|A_M| \leq 2|G_M|$.

Since $\{a + a' : (a, a') \in G\}$ and $\{a - a' : (a, a') \in G\}$ are subsets of $\{2b : b \in B\}$, they have $\leq k$ elements; and $\{aa' : (a, a') \in G\} \subset M$. Therefore (3.2) implies that $|G_M|^{1-\varepsilon} \ll_\varepsilon |M| + k$. Since, trivially, $|G_M| \leq k^2$ we have $\sum_{m \in M} r_{E-E}(m) = |G_M| \ll k^{2\varepsilon}(|M| + k)$.

Now let M be the set of integers m for which $r_{E-E}(m) \geq k^{3\varepsilon}$, so that $\sum_{m \in M} r_{E-E}(m) \geq k^{3\varepsilon}|M|$ and hence $\sum_{m \in M} r_{E-E}(m) \ll k^{1+2\varepsilon}$ by combining the last two equations. Therefore, as $r_{E-E}(m) \leq k$,

$$\|f_E\|_4^4 = \sum_m r_{E-E}(m)^2 \leq \sum_{m \in E-E} k^{6\varepsilon} + k \sum_{m \in M} r_{E-E}(m) \ll k^{2+6\varepsilon}.$$

She also proves a further, and stronger result along similar lines:

Conjecture 8 (Mei-Chu Chang). *If A is a finite set of integers and $G \subset A \times A$ then*

$$(3.3) \quad |\{a + b : (a, b) \in G\}| \cdot |\{a - b : (a, b) \in G\}| \cdot |\{ab : (a, b) \in G\}| \gg_\varepsilon |G|^{2-\varepsilon}.$$

Theorem 9. *Conjecture 8 holds if and only if Conjecture 4 holds.*

Proof: Assume Conjecture 8 and define B, A and G_M as in the proof of theorem 8, so that $(\sum_{m \in M} r_{E-E}(m))^2 = |G_M|^2 \ll k^{2+2\varepsilon}|M|$. We partition $E - E$ into the sets $M_j := \{m : 2^{j-1} \leq r_{E-E}(m) < 2^j\}$ for $j = 1, 2, \dots, J := \lceil \log(2k)/\log 2 \rceil$; then $(2^{j-1}|M_j|)^2 \leq (\sum_{m \in M_j} r_{E-E}(m))^2 \ll k^{2+2\varepsilon}|M_j|$ so that $\sum_{m \in M_j} r_{E-E}(m)^2 \leq 2^{2j}|M_j| \ll k^{2+2\varepsilon}$. Hence

$$\|f_E\|_4^4 = \sum_m r_{E-E}(m)^2 < \sum_j \sum_{m \in M_j} r_{E-E}(m)^2 \ll Jk^{2+2\varepsilon} \ll k^{2+3\varepsilon},$$

as desired.

Now assume Conjecture 4 and let $G_n := \{(a, b) \in G : ab = n\}$. Then $|G|^2 = (\sum_n |G_n|)^2 \leq |\{ab : (a, b) \in G\}| \cdot \sum_n |G_n|^2$, while

$$\sum_n |G_n|^2 = \int_0^1 \left| \sum_{(a,b) \in G} e(4abt) \right|^2 dt = \int_0^1 \left| \sum_{(a,b) \in G} e((a+b)^2 t) e(-(a-b)^2 t) \right|^2 dt$$

which, letting $E_\pm := \{r^2 : r = a \pm b, (a, b) \in G\}$, is

$$\leq \int_0^1 \left| \sum_{r^2 \in E_+} e(r^2 t) \sum_{s^2 \in E_-} e(-s^2 t) \right|^2 dt \leq \|f_{E_+}\|^2 \|f_{E_-}\|^2$$

by the Cauchy-Schwarz inequality. Since $\|f_{E_\pm}\|^2 \ll |\{a \pm b : (a, b) \in G\}| \cdot |G|^{2\varepsilon}$ by Conjecture 4, our result follows by combining the above information.

4. SOLUTIONS OF A QUADRATIC CONGRUENCE IN SHORT INTERVALS

We begin with a connection between additive combinatorics and the Chinese Remainder Theorem. Suppose that $n = rs$ with $(r, s) = 1$; and that for given sets of residues $\Omega(r) \subset \mathbb{Z}/r\mathbb{Z}$ and $\Omega(s) \subset \mathbb{Z}/s\mathbb{Z}$ we have $\Omega(n) \subset \mathbb{Z}/n\mathbb{Z}$ in the sense that $m \in \Omega(n)$ if and only if there exists $u \in \Omega(r)$ and $v \in \Omega(s)$ such that $m \equiv u \pmod{r}$ and $m \equiv v \pmod{s}$. When $(r, n/r) = 1$ consider the map which embeds $\mathbb{Z}/r\mathbb{Z} \rightarrow \mathbb{Z}/n\mathbb{Z}$ by taking $u \pmod{r}$ and replaces it by $U \pmod{n}$ for which $U \equiv u \pmod{r}$ and $U \equiv 0 \pmod{n/r}$; we denote by $\Omega(r, n)$ the image of $\Omega(r)$ under this map. The key remark, which follows immediately from the definitions, is that

$$\Omega(n) = \Omega(r, n) + \Omega(s, n).$$

Thus if $n = p_1^{e_1} \dots p_k^{e_k}$ where the primes p_i are distinct then

$$\Omega(n) = \Omega(p_1^{e_1}, n) + \Omega(p_2^{e_2}, n) + \dots + \Omega(p_k^{e_k}, n).$$

Particularly interesting is where $\Omega_f(n)$ is the set of solutions $m \pmod{n}$ to $f(m) \equiv 0 \pmod{n}$, for given $f(x) \in \mathbb{Z}[x]$. We are mostly interested in deciding when there are many elements of $\Omega_f(n)$ in a short interval where f has degree two. *A priori* this seems unlikely since the elements of the $\Omega(r, n)$ are so well spread out, that is they have a distance $\geq n/r$ between any pair of elements because they are all divisible by n/r .

The next theorem involves the distribution of the elements of $\Omega(n)$ in the simplest non-trivial case, in which each $\Omega(p_j^{e_j})$ has just two elements, namely $\{0, 1\}$, so that $\Omega(n)$ is the set of solutions of $x(x-1) \equiv 0 \pmod{n}$ (see also [3]).

Theorem 10. *Let $\Omega(n)$ be the set of solutions of $x(x-1) \equiv 0 \pmod{n}$. Then*

- (1) $\Omega(n)$ has an element in the interval $(1, n/k + 1)$.
- (2) For any $\varepsilon > 0$ there exists $n = p_1 \dots p_k$ such that $\Omega(n) \cap (1, (\frac{1}{k} - \varepsilon)n] = \emptyset$.
- (3) For any $\varepsilon > 0$ there exists $n = p_1 \dots p_k$ such that if $x \in \Omega(n)$ then $|x| < \varepsilon n$.

Proof. Let $\Omega(p_j^{e_j}, n) = \{0, x_j\}$ where $x_j \equiv 1 \pmod{p_j^{e_j}}$ and $x_j \equiv 0 \pmod{p_i^{e_i}}$ for any $i \neq j$. Then $\Omega(n) = \{0, x_1\} + \dots + \{0, x_k\}$. Let $s_0 = n$ and s_r be the least positive residue of $x_1 + \dots + x_r \pmod{n}$ for $r = 1, \dots, k$ so that $s_k = 1$. By the pigeonhole principle, there exists $0 \leq l < m \leq k$ such that s_l and s_m lie in the same interval $(jn/k, (j+1)n/k]$, and so $|s_l - s_m| < n/k$ with $s_m - s_l \equiv x_{l+1} + \dots + x_m \pmod{n} \in \Omega(n)$. If $s_m - s_l > 1$ then

we are done. Now $s_k - s_0 \equiv 1 \pmod{n}$ but is not $= 1$, so $s_m - s_l \neq 0, 1$. Thus we must consider when $s_m - s_l < 0$. In this case $x_1 + \cdots + x_l + x_{m+1} + \cdots + x_k \pmod{n} \in \Omega(n)$ and is $\equiv s_k - (s_m - s_l) \equiv 1 - (s_m - s_l)$, and the result follows.

To prove (2) let us take $k-1$ primes $p_1, \dots, p_{k-1} > k$, and integers $a_j = [p_j/k]$ for $j = 1, \dots, k-1$. Let $P = p_1 \cdots p_{k-1}$ and determine $r \pmod{P}$ by the Chinese Remainder Theorem satisfying $ra_j(P/p_j) \equiv 1 \pmod{p_j}$ for $j = 1, \dots, k-1$. Now let p_k be a prime $\equiv r \pmod{P}$, and let a_k the least positive integer satisfying $a_k P \equiv 1 \pmod{p_k}$. Let $n = p_1 \cdots p_k$ so that $x_i = a_i n/p_i$ for $i = 1, \dots, k$. Now $n/k \geq x_i > n/k - n/p_i > 0$ for $i = 1, \dots, k-1$ and since $x_1 + \cdots + x_k \equiv 1 \pmod{n}$ with $1 \leq x_k < n$ we deduce that $x_1 + \cdots + x_k = n+1$ and therefore $1 + n/k \leq x_k < 1 + n/k + n \sum_{i=1}^{k-1} 1/p_i$. Now elements of $\Omega(n)$ are of the form $\sum_{i \in I} x_i$ and we have $|\sum_{i \in I} x_i - n|I|/k| \leq 1 + 2n \sum_{i=1}^{k-1} 1/p_i$, and this is $< \varepsilon n$ provided $p_i > 2k/\varepsilon$ for each p_i . Finally, since the cases $I = \emptyset$ and $I = \{1, \dots, k\}$ correspond to the cases $x = 0$ and $x = 1$ respectively, we have that any other element is greater than $(1/k - \varepsilon)n$.

To prove (3) we mimic the proof of (2) but now choosing non-zero integers a_j satisfying $|\frac{a_j}{p_j}| < \frac{\varepsilon}{2k}$ for $j = 1, \dots, k-1$. This implies that $|a_k/p_k| < \varepsilon/2$ and then $|\sum_{i \in I} x_i| < \varepsilon n$.

In the other direction, we give a lower bound for the length of intervals containing k elements of $\Omega(n)$.

Theorem 11. *Let integer $d \geq 2$ be given, and suppose that for each prime power q we are given a set of residues $\Omega(q) \subset (\mathbb{Z}/q\mathbb{Z})$ which contains no more than d elements. Let $\Omega(n)$ be determined for all integers n using the Chinese Remainder Theorem, as described at the start of this section. Then, for any $k \geq d$, there are no more than k integers $x \in \Omega(n)$ in any interval of length $n^{\alpha_d(k)}$, where $\alpha_d(k) = \frac{1 - \varepsilon_d(k)}{d} > 0$ with $0 < \varepsilon_d(k) = \frac{d-1}{k} + O(\frac{d^2}{k^2})$.*

Proof. Let x_1, \dots, x_{k+1} elements of $\Omega(n)$ such that $x_1 < \cdots < x_{k+1} < x_1 + n^{\alpha_d(k)}$. Let q a prime power dividing n . Each x_i belongs to one of the d classes \pmod{q} in $\Omega(q)$. Write r_1, \dots, r_d to denote the number of these x_i belonging to each class. Then $\prod_{1 \leq i < j \leq k+1} (x_j - x_i)$ is a multiple of $q^{\sum_{i=1}^d \binom{r_i}{2}}$. The minimum of $\sum_{i=1}^d \binom{r_i}{2}$ under the restriction $\sum_i r_i = k+1$ is $d \binom{r}{2} + rs$ where r, s are determined by $k+1 = rd+s$, $0 \leq s < d$. Finally

$$n^{\alpha_d(k) \binom{k+1}{2}} > \prod_{1 \leq i < j \leq k+1} (x_i - x_j) > n^{d \binom{r}{2} + rs}$$

and we get a contradiction, by taking $\alpha_d(k) = (d \binom{r}{2} + rs) / \binom{k+1}{2}$.

The next theorem is an easy consequence of the proof above.

Theorem 12. *If $x_1 < \cdots < x_k$ are solutions to the equation $x_i^2 \equiv a \pmod{b}$, then $x_k - x_1 > b^{\frac{1}{2} - \frac{1}{2\ell}}$, where ℓ is the largest odd integer $\leq k$.*

First proof. For any maximal prime power q dividing b , (a, q) must be a square so we can write $x_i = y_i \prod_q (a, q)^{1/2}$ with $y_i^2 \equiv a' \pmod{q'}$ where $q' = q/(a, q)$ and $(a', q') = 1$. Let $\Omega(q')$ be the solutions of $y^2 \equiv a' \pmod{q'}$. Now, since $(a', q') = 1$ we have that

$|\Omega(q')| \leq 2$ and we can apply theorem 11 to obtain that

$$x_k - x_1 = (y_k - y_1) \prod_q (a, q)^{1/2} \geq \left(\prod_q q/(a, q) \right)^{\alpha_2(k-1)} \prod_q (a, q)^{1/2} \geq \left(\prod_q q \right)^{\alpha_2(k-1)}.$$

Now, notice that $\alpha_2(k-1) = 1/2 - 1/(2l)$ where l is the largest odd number $\leq k$.

Second proof. Write $x_j^2 = a + r_j b$ where $r_1 = 1 < r_2 < \dots < r_k$ (if necessary, by replacing a in the hypothesis by $x_1^2 - b$). Consider the k -by- k Vandermonde matrix V with (i, j) th entry x_j^{i-1} . The row with $i = 1 + 2I$ has j th entry $(a + r_j b)^I$; by subtracting suitable multiples of the rows $1 + 2\ell$, $\ell < I$, we obtain a matrix V_1 with the same determinant where the $(2I + 1, j)$ entry is now $(r_j b)^I$. Similarly the row with $i = 2I + 2$ has j th entry $x_j(a + r_j b)^I$; by subtracting suitable multiples of the rows $2 + 2\ell$, $\ell < I$, we obtain a matrix V_2 with the same determinant where the $(2I + 2, j)$ entry is now $x_j(r_j b)^I$. Finally we arrive at a matrix W by dividing out b^I from rows $2I + 1$ and $2I + 2$ for all I . Then the determinant of V , which is $\prod_{1 \leq i < j \leq k} (x_j - x_i)$, equals $b^{[(k-1)^2/4]}$ times the determinant of W , which is also an integer, and the result follows.

The advantage of this new proof is that if we can get non-trivial lower bounds on the determinant of W then we can improve Theorem 12. We note that W has $(2I + 1, j)$ entry r_j^I , and $(2I + 2, j)$ entry $x_j r_j^I$.

Remark: Taking $k = \ell$ to be the smallest odd integer $\geq \frac{\log b}{\log 4}$, then we can split our interval into two pieces to deduce from Theorem 12 a weak version of Conjecture 9: There are no more than $\frac{\log 4b}{\log 2}$ solutions x to the equation $x^2 \equiv a \pmod{b}$ in any interval of length $b^{1/2}$. From this it follows that the number of solutions x to the equation $x^2 \equiv a \pmod{b}$ in any interval of length L is

$$\ll 1 + \frac{\log L}{\log \left(1 + \frac{b^{1/2}}{L} \right)}.$$

This result, with ‘1/2’ replaced by ‘1/d’, was proved for the roots of any degree d polynomial mod b by Konyagin and Steger in [23].

A slightly improvement on the theorem above would have interesting consequences.

Conjecture 9. *There exists a constant N such that there are no more than N solutions $0 < x_1 < x_2 < \dots < x_N < x_1 + b^{1/2}$ to the equation $x_i^2 \equiv a \pmod{b}$, for any given a and b .*

Theorem 13. *Conjecture 9 implies Conjecture 1.*

Proof. Suppose that there are $\ell \gg k^{1/2}$ squares amongst $a + b, a + 2b, \dots, a + kb$, which we will denote $x_1^2 < x_2^2 < \dots < x_\ell^2$. By conjecture 9 we have $x_\ell - x_1 \geq [(\ell - 1)/N]b^{1/2}$, whereas $(k - 1)b \geq (x_\ell + x_1)(x_\ell - x_1) \geq (x_\ell - x_1)^2$. Therefore $[(\ell - 1)/N]^2 \leq (k - 1)$ which implies that $\ell \leq N(1 + \sqrt{k - 1})$.

Conjecture 9 would follow easily from theorem 11 if we could get the exponent $1/2$ for some k , instead of $1/2 - \varepsilon_2(k)$. Conjecture 9 can be strengthened and generalized as follows:

Conjecture 10. *Let integer $d \geq 1$ be given, and suppose that for each prime power q we are given a set of residues $\Omega(q) \subset (\mathbb{Z}/q\mathbb{Z})$ which contains no more than d elements. $\Omega(b)$ is determined for all integers b using the Chinese Remainder Theorem, as described at the start of this section. Then, for any $\varepsilon > 0$ there exists a constant $N(d, \varepsilon)$ such that for any integer b there are no more than $N(d, \varepsilon)$ integers n , $0 \leq n < b^{1-\varepsilon}$ with $n \in \Omega(b)$.*

In theorem 11 we proved such a result with the exponent ‘ $1 - \varepsilon$ ’ replaced by ‘ $1/d - \varepsilon$ ’. We strongly believe Conjecture 10 with ‘ $1 - \varepsilon$ ’ replaced by ‘ $1/d$ ’, analogous to Conjecture 9. In a 1995 email to the second author, Bjorn Poonen asked Conjecture 10 with ‘ $1 - \varepsilon$ ’ replaced by ‘ $1/2$ ’ for $d = 4$; his interest lies in the fact that this would imply the uniform boundedness conjecture for rational preperiodic points of quadratic polynomials (see [25]).

Conjecture 10 does not cover the case $\Omega_f(b) = \{m \pmod{b} : f(m) \equiv 0 \pmod{b}\}$ for all monic polynomials f of degree d since, for example, the polynomial $(x - a)^d \equiv 0 \pmod{p^k}$ has got $p^{k - \lceil k/d \rceil}$ solutions $\pmod{p^k}$, rather than d . One may avoid this difficulty by restricting attention to squarefree moduli (as in a conjecture posed by Croot [19]); or, to be less restrictive, note that if $f(x)$ has more than d solutions $\pmod{p^k}$ then f must have a repeated root mod p , so that p divides the discriminant of f :

Conjecture 11. *Fix integer $d \geq 2$. For any $\varepsilon > 0$ there exists a constant $N(d, \varepsilon)$ such that for any monic $f(x) \in \mathbb{Z}[x]$ there are no more than $N(d, \varepsilon)$ integers n , $0 \leq n < b^{1-\varepsilon}$, with $f(n) \equiv 0 \pmod{b}$ for any integer b such that if p^2 divides b then p does not divide the discriminant of f .*

5. LATTICE POINTS ON CIRCLES

Conjecture 12. *There exists $\delta > 0$ and integer $m > 0$ such that if $a_i^2 + b_i^2 = n$ with $a_i, b_i > 0$ and $a_i^2 \equiv a_1^2 \pmod{q}$ for $i = 1, \dots, m$ then $q = O(n^{1-\delta})$.*

Theorem 14. *Conjecture 12 implies Conjecture 1*

Proof. Suppose that $x_1^2 < \dots < x_r^2$ are distinct squares belonging to the arithmetic progression $a + b, a + 2b, \dots, a + kb$ with $(a, b) = 1$, where $r > \sqrt{8lk}$, with l sufficiently large $> m$. We may assume that $(a, b) = 1$ and that b is even. There are r^2 sums $x_i^2 + x_j^2$ each of which takes one of the values $2a + 2b, 2a + 3b, \dots, 2a + 2kb$, and so one of these values, say n , is taken $\geq r^2/(2k - 1) > 4l$ times. Therefore we can write $n = r_j^2 + s_j^2$ for $j = 1, 2, \dots, 4l$ for distinct pairs (r_j, s_j) , and let $v_j = r_j + is_j$. Note that $n \equiv 2 \pmod{8}$. Let $\Pi = \prod_{1 \leq i < j \leq 4l} (v_j - v_i) \neq 0$. We will prove that $|\Pi| \geq b^{4 \binom{l}{2}} (n/2)^{\binom{2l}{2}}$, by considering the powers of the prime divisors of b and n which divide Π . Note that $(n/2, b) = 1$.

Suppose $p^e \parallel b$ where p is a prime, and select $w \pmod{p^e}$ so that $w^2 \equiv a \pmod{p^e}$. Note that each $r_j, s_j \equiv w$ or $-w \pmod{p^e}$: We partition the v_j into four subsets J_1, J_2, J_3, J_4 depending on the value of $(r_j \pmod{p^e}, s_j \pmod{p^e})$. Note then that p^e divides $v_j - v_i$ if v_i, v_j belong to the same subset, and so p^e to the power $\sum_i \binom{|J_i|}{2} > 4 \binom{l}{2}$ divides Π .

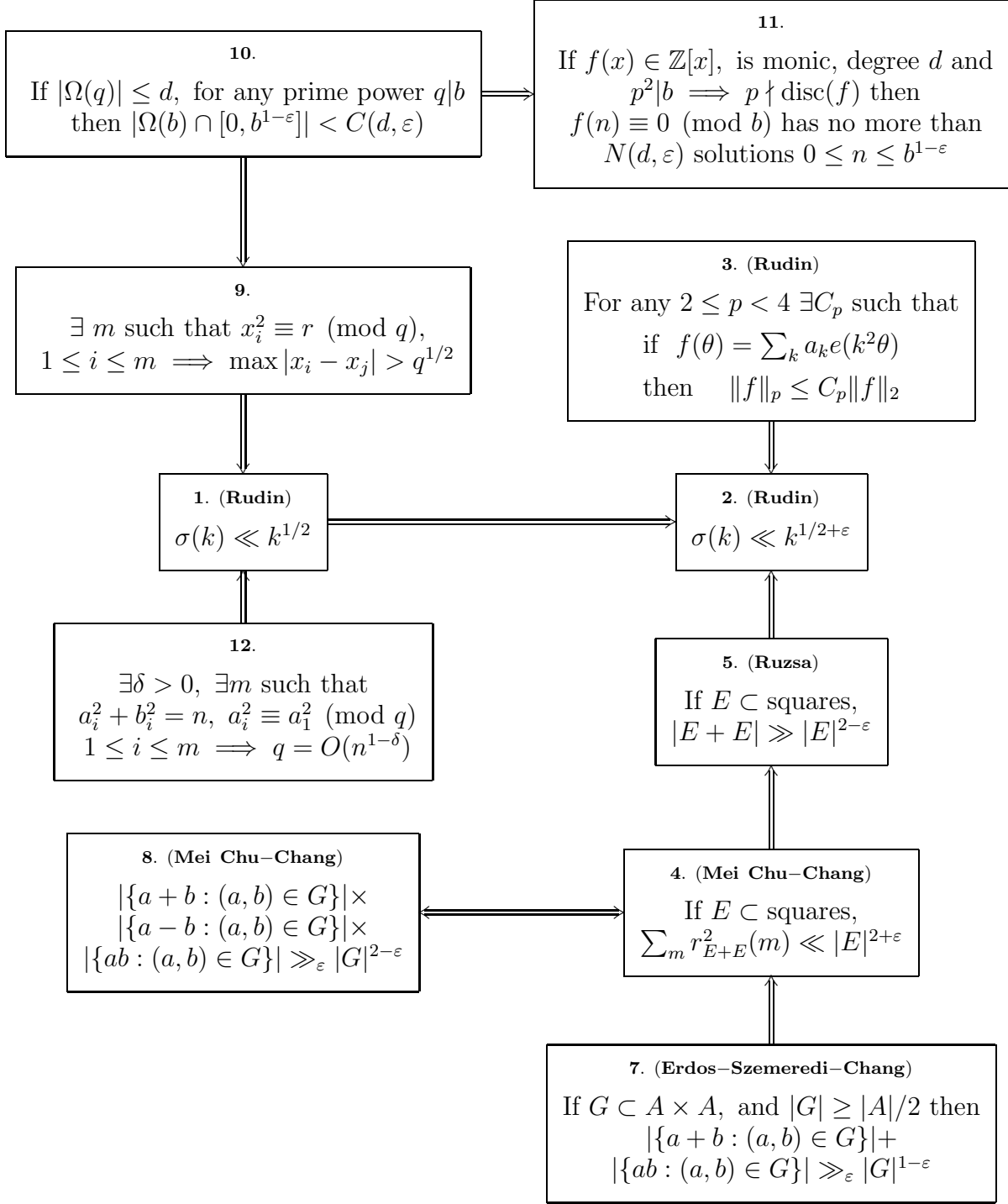
Now let p be an odd prime with $p^e \parallel n$. If $p \equiv 3 \pmod{4}$ then $p^{e/2}$ must divide each r_j and s_j so that then $p^{(e/2) \binom{4l}{2}}$ divides Π . If $p \equiv 1 \pmod{4}$ let us suppose π is a prime in $\mathbb{Z}[i]$ dividing p ; then $\pi^{e_j} \bar{\pi}^{e-e_j}$ divides v_j for some $0 \leq e_j \leq e$. If $e_i \leq e_j$ we deduce that

$\pi^{e_i} \bar{\pi}^{e-e_j}$ divides $v_j - v_i$. We now partition the values of j into sets J_0, \dots, J_e depending on the value of e_j . The power of π dividing Π is thus $\sum_{i=0}^e i \sum_{g=i+1}^e |J_i| |J_g| + \sum_{i=0}^e (e-i) \binom{|J_i|}{2}$, and the power of $\bar{\pi}$ dividing Π is thus $\sum_{i=0}^e (e-g) \sum_{i=0}^{g-1} |J_i| |J_g| + \sum_{i=0}^e (e-i) \binom{|J_i|}{2}$. It is easy to show that $\sum_{0 \leq i < g \leq e} (i+e-g) m_i m_g + e \sum_{i=0}^e \binom{m_i}{2}$, under the conditions that $\sum_i m_i$ is fixed and each $m_i \geq 0$, is minimized when $m_0 = m_e$, $m_1 = \dots = m_{e-1} = 0$. Therefore the power of π plus the power of $\bar{\pi}$ dividing Π is $\geq 2e \binom{2l}{2}$.

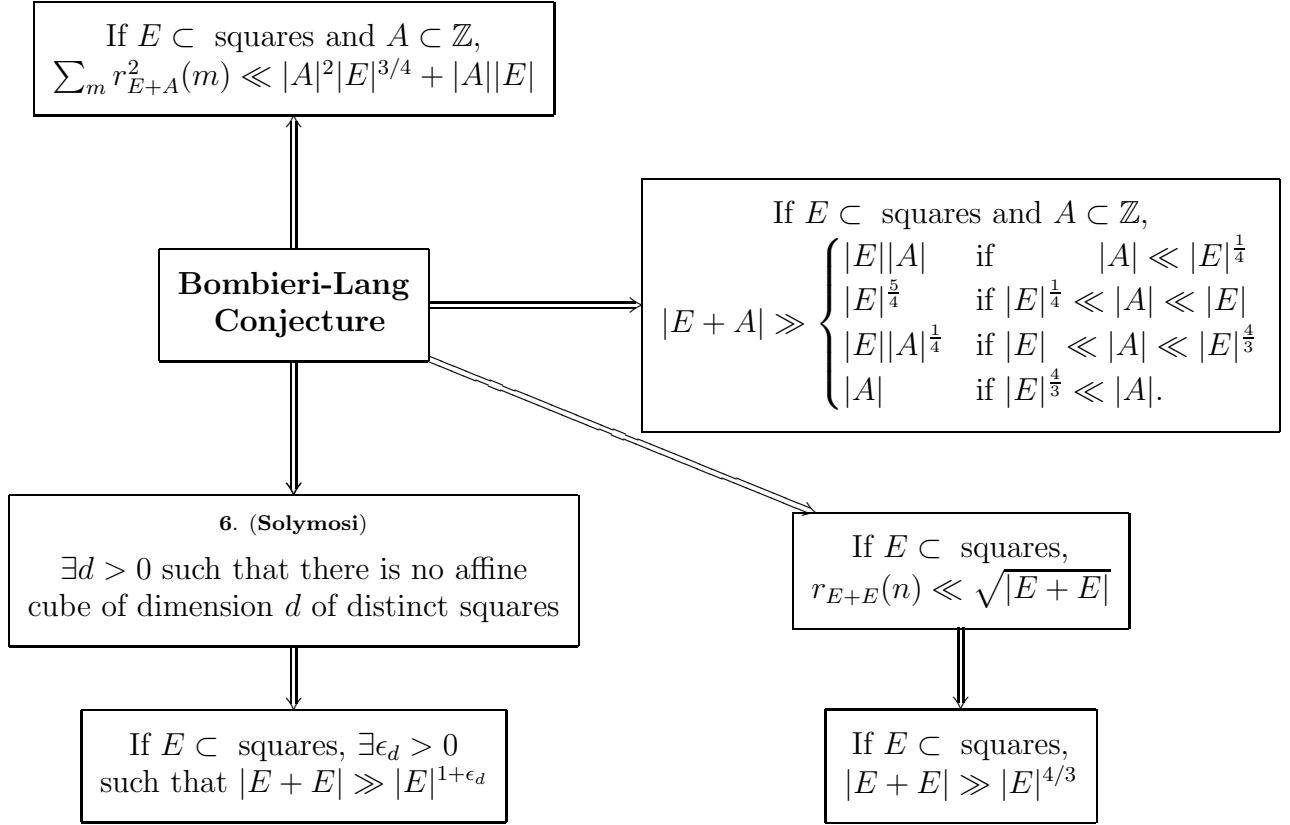
Finally $|r_j - r_i|, |s_j - s_i| \leq (x_r^2 - x_1^2)/(x_r + x_1) \leq (k-1)b/(2\sqrt{a+b})$, and so $|v_j - v_i|^2 \leq (k-1)^2 b^2 / (2(a+b))$, giving that $|\Pi| \leq (k^2 b^2 / (2(a+b)))^{(1/2) \binom{4l}{2}}$. Putting these all together with the fact that $n > 2(a+b)$, we obtain $2^{2l-1} (a+b)^{3l-1} \leq k^{4l-1} b^{3l}$. However this implies that $n \leq 2k(a+b) \leq 2^{1/2} k^{5/2} b^{1+1/(3l-1)} \ll k^{5/2} n^{(1+1/(3l-1))(1-\delta)} \ll k^{5/2} n^{1-\delta/2}$, for l sufficiently large; and therefore $a+b < n \ll k^{O(1)}$.

Let u_1, \dots, u_d be the distinct integers in $[1, b/2]$ for which each $u_j^2 \equiv a \pmod{b}$, so that $d \asymp 2^{\omega(b)}$, by the Chinese Remainder Theorem, where $\omega(b)$ denotes the number of prime factors of b . The number of $x_i \equiv u_j \pmod{b/2}$ is $\leq 1 + ((a+kb)^{1/2} - a^{1/2})/(b/2) \leq 1 + 2(k/b)^{1/2}$; and thus $r \ll 2^{\omega(b)} + k^{1/2} 2^{\omega(b)} / b^{1/2}$. This is $\ll k^{1/2}$ provided $\omega(b) \ll \log k$, which happens when $b \ll k^{O(\log \log k)}$ by the prime number theorem. The result follows.

Here is a flowchart of the relationships between the conjectures above:



Dependencies: $\varepsilon_2 = \varepsilon_5/(4 - 2\varepsilon_5)$, $\varepsilon_2 = 2/p - 1/2$, $\varepsilon_4 = 3\varepsilon_7/2$, $\varepsilon_4 = 3\varepsilon_8/4$, $\varepsilon_5 = \varepsilon_4$, $\varepsilon_8 = 4\varepsilon_4$.



Conjecture 13. For any $\alpha < 1/2$, there exists a constant C_α such that for any N we have

$$\#\{(a, b), a^2 + b^2 = n, N \leq |b| < N + n^\alpha\} \leq C_\alpha.$$

A special case of interest is where $N = 0$:

$$(5.1) \quad \#\{(a, b), a^2 + b^2 = n, |b| < n^\alpha\} \leq C_\alpha.$$

Heath-Brown pointed out that one has to be careful in making an analogous conjecture in higher dimension as the following example shows: Select integer r which has many representations as the sum of two squares; for example, if r is the product of k distinct primes that are $\equiv 1 \pmod{4}$ then r has 2^k such representations. Now let N be an arbitrarily large integer and consider the set of representations of $n = N^2 + r$ as the sum of three squares. Evidently we have $\geq 2^k$ such representations in an interval whose size, which depends only on k , is independent of n . However, one can get around this kind of example in formulating the analogy to conjecture 13 in 3-dimensions, since all of these solutions live in a fixed hyperplane. Thus we may be able to get a uniform bound on the number of such lattice points in a small box, no more than three of which belong to the same hyperplane.

It is simple to prove (5.1) for any $\alpha \leq 1/4$ (and Conjecture 13 for $\alpha \leq 1/4$ with $N \ll n^{\frac{1}{2}-\alpha}$), but we cannot prove (5.1) for any $\alpha > 1/4$. Conjecture 13 and the special case 5.1 are equivalent to the following conjectures respectively:

Conjecture 14. The number of lattice points $\{(x, y) \in \mathbb{Z}^2 : x^2 + y^2 = R^2\}$ in an arc of length $R^{1-\varepsilon}$ is bounded uniformly in R .

Conjecture 15. *The number of lattice points $\{(x, y) \in \mathbb{Z}^2 : x^2 + y^2 = R^2\}$ in an arc of length $R^{1-\varepsilon}$ around the diagonal is bounded uniformly in R .*

Conjectures 13 and 14 are just a rephrasing of one another, and obviously imply (5.1) and Conjecture 15. In the other direction, if we have points $\alpha_j := x_j + iy_j$ on $x^2 + y^2 = R^2$ in an arc of length $R^{1-\varepsilon}$ then we have points $\alpha_j \bar{\alpha}_0 = a_j + ib_j$ satisfying $a_j^2 + b_j^2 = R^2$ with $|b_j| \ll R^{1-\varepsilon}$ contradicting (5.1), and we have points $(1+i)\alpha_j \bar{\alpha}_0$ on $x^2 + y^2 = 2R^2$ in an arc of length $\ll R^{1-\varepsilon}$ around the diagonal, contradicting Conjecture 15.

The following result is proved in [15]:

Theorem 15. *There are no more than k lattice points $\{(x, y) \in \mathbb{Z}^2 : x^2 + y^2 = R^2\}$ in an arc of length $R^{\frac{1}{2} - \frac{1}{4\lfloor k/2 \rfloor + 2}}$.*

Proof. We may assume that $R^2 = \prod_{p \equiv 1 \pmod{4}} p^e$, as the result for general R^2 is easily deduced from this case. Let $\mathbf{p}\bar{\mathbf{p}}$ be the Gaussian factorization of p . Then each lattice point ν_i , $1 \leq i \leq k+1$ can be identified with a divisor of R^2 of the form $\nu_i = \prod_{\mathbf{p}} \mathbf{p}^{e_i} \bar{\mathbf{p}}^{e-e_i}$. Therefore $\nu_i - \nu_j$ is divisible by $\mathbf{p}^{\min\{e_i, e_j\}} \bar{\mathbf{p}}^{\min\{e-e_i, e-e_j\}}$, so that $|\nu_i - \nu_j|^2$ is divisible by $p^{e-|e_i-e_j|}$. Hence, since $\sum_{1 \leq i < j \leq k+1} |e_i - e_j| \leq e \lfloor \frac{k+1}{2} \rfloor (k - \lfloor \frac{k+1}{2} \rfloor)$, we have

$$\prod_{1 \leq i < j \leq k+1} |\nu_i - \nu_j|^2 \geq \prod_p p^{\sum_{1 \leq i < j \leq k+1} e - |e_i - e_j|} \geq \left(\prod_p p^e \right)^{\binom{k+1}{2} - \lfloor \frac{k+1}{2} \rfloor (k - \lfloor \frac{k+1}{2} \rfloor)}$$

and the result follows.

It seems to be a difficult problem to decide whether the exponent $\frac{1}{2} - \frac{1}{4\lfloor k/2 \rfloor + 2}$ is sharp for each k in Theorem 15. We know that it is sharp for $k = 1, 2, 3$ but we don't know what happens for larger k . More precisely:

- (1) Obviously an arc of length $\sqrt{2}$ contains no more than one lattice point; whereas the lattice points $(n, n+1), (n+1, n)$ lie on an arc of length $\sqrt{2} + o(1)$.
- (2) It was shown in [14] that an arc of length $(16R)^{1/3}$ contains no more than two lattice points. On the other hand the lattice points $(4n^3-1, 2n^2+2n), (4n^3, 2n^2+1), (4n^3+1, 2n^2-2n)$ lie on an arc of length $(16R_n)^{1/3} + o(1)$.
- (3) It was shown in [17] that an arc of length $(40 + \frac{40}{3}\sqrt{10})^{1/3} R^{1/3}$, with $R > \sqrt{65}$, contains no more than three lattice points, whereas there exists an infinite family of circles $x^2 + y^2 = R_n^2$ containing four lattice points on an arc of length $(40 + \frac{40}{3}\sqrt{10})^{1/3} R_n^{1/3} + o(1)$. Other than in the examples arising from this family, an arc of length $(40 + 20\sqrt{5})^{1/3} R^{1/3}$ contains no more than three lattice points, whereas the four lattice points $(x_0 - 2G_{n-2}, y_0 - 2G_{n+1}), (x_0 + G_{n-3}, y_0 + G_n), (x_0 + G_{n-2}, y_0 + G_{n+1}), (x_0 - G_{n-1}, y_0 - G_{n+2})$, where $x_0 := \frac{1}{2}F_{3n+2}$, $y_0 = \frac{1}{2}F_{3n-1}$, $G_m = (-1)^m F_m$ and F_m is the m th Fibonacci number, lie on the circle $x^2 + y^2 = \frac{5}{2}F_{2n-2}F_{2n}F_{2n+2} = R_n^2$ on an arc of length $(40 + 20\sqrt{5})^{1/3} R_n^{1/3} + o(1)$.
- (4) Theorem 15 is the best result known for all $k \geq 4$. In particular it implies that an arc of length $R^{2/5}$ contains at most 4 lattice points, and we do not know whether the exponent $2/5$ can be improved: Are there infinitely many circles $x^2 + y^2 = R_n^2$ with four lattice points on an arc of length $\ll R_n^{2/5}$?

6. INCOMPLETE TRIGONOMETRIC SUMS OF SQUARES

The L_4 norm of a trigonometric polynomial has an interesting number theory interpretation. For $f(\theta) = \sum_{n_k \in E} a_k e(n_k \theta)$ we can write

$$\begin{aligned} \|f\|_4^4 &= \int_0^1 \left| \sum_k a_k e(n_k \theta) \right|^4 d\theta = \int_0^1 \left| \sum_m \left(\sum_{n_k+n_j=m} a_k a_j \right) e(m\theta) \right|^2 d\theta \\ &= \sum_m \left| \sum_{n_k+n_j=m} a_k a_j \right|^2 \leq \sum_m r_{E+E}(m) \sum_{n_k+n_j=m} |a_k|^2 |a_j|^2 \\ &\leq \left(\sum_k |a_k|^2 \right)^2 \max_m r_{E+E}(m) \end{aligned}$$

using the Cauchy-Schwarz inequality to obtain the first inequality, so that

$$(6.1) \quad \|f\|_4 \leq \|f\|_2 \left(\sum_k \max_m r_{E+E}(m) \right)^{1/4}.$$

If E is the set of squares then $r_{E+E}(m) \leq \tau(m) \ll m^\varepsilon$; so, by (6.1), we have

$$\|f\|_4 \ll N^\varepsilon \|f\|_2$$

for any E -polynomial f where $E = \{1^2, \dots, N^2\}$. Bourgain [6] conjectured the more refined:

Conjecture 16. *There exists a constant δ such that for any E -polynomial f where $E = \{1^2, \dots, N^2\}$, we have*

$$\|f\|_4 \ll \|f\|_2 (\log N)^\delta.$$

Note that δ must be $\geq 1/4$; since we saw, in the second section, that $\|f\|_4 \sim C(\log N)^{1/4} \|f\|_2$ for $f(\theta) = \sum_{1 \leq k \leq N} e(k^2 \theta)$.

The corresponding conjecture when $f(\theta) = \sum_{k \in E} e(k^2 \theta)$ and $E \subset \{1^2, \dots, N^2\}$ is the following.

Conjecture 17. *There exists $C > 0$ such that if $E \subset \{1^2, \dots, N^2\}$ then $\sum_m r_{E+E}^2(m) \ll |E|^2 (\log N)^C$.*

Actually we can prove that both conjectures are equivalents.

Theorem 16. *Conjectures 16 and 17 are equivalent.*

Proof: Conjecture 17 is a special case of Conjecture 16, so we must prove that Conjecture 16 follows from Conjecture 17. We may divide the coefficients of f by $\|f\|_2$ to ensure that $\|f\|_2 = (\sum_k |a_k|^2)^{1/2} = 1$, and therefore every $|a_k| \leq 1$. Define $E_0 = \{k, |a_k| \leq N^{-1}\}$ and $E_j = \{k, 2^{j-1}/N < |a_k| \leq 2^j/N\}$ for all $j \geq 1$. Since $f = \sum_{j \geq 0} f_j$ (where each f_j is the appropriate E_j -polynomial), we have $\|f\|_4 \leq \sum_{j \geq 0} \|f_j\|_4$ by the triangle inequality. By Conjecture 17 we have

$$\|f_j\|_4^4 = \sum_n \left| \sum_{\substack{k^2+j^2=n \\ k,j \in E_j}} a_k a_j \right|^2 \leq (2^j/N)^4 \sum_n r_{E_j+E_j}^2(n) \ll (\log N)^C (2^j/N)^4 |E_j|^2.$$

Now $\sum_{k \in E_j} |a_k|^2 \asymp |E_j|(2^{2j}/N^2)$ for all $j \geq 1$, and $|E_0|/N^2$, $\sum_{k \in E_0} |a_k|^2 \ll 1/N$, which imply that $\sum_{j \geq 0} |E_j|(2^{2j}/N^2) \asymp 1$. Since $|E_j| = 0$ for $j > \lceil \log_2 N \rceil$, we deduce that

$$\frac{1}{(\log N)^{C/4}} \sum_{j \geq 0} \|f_j\|_4 \ll \sum_{j \geq 0} \frac{2^j |E_j|^{1/2}}{N} \ll \left(\sum_{j=0}^{\lceil \log_2 N \rceil} 1 \sum_{j \geq 1} \frac{2^{2j} |E_j|}{N^2} \right)^{1/2} \ll (\log N)^{1/2}.$$

Therefore Conjecture 16 follows with $\delta = C/4 + 1/2$.

Also we prove the following related result which slightly improves on Theorem 2 of [15].

Theorem 17. *If $E = \{k^2 : N \leq k \leq N + \Delta\}$ with $\Delta \leq N$ and $f(\theta) = \sum_{r \in E} e(r\theta)$, so that $\|f\|_2^2 \sim \Delta$, then*

$$\|f\|_4^4 \asymp \Delta^2 + \Delta^3 \cdot \frac{\log N}{N}.$$

In particular, $\|f\|_4 \ll \|f\|_2$ if and only if $\Delta \ll (\log N)/N$.

Proof: Note that $\|f\|_2^2 = |E|$ and

$$\|f\|_4 = \sum_n r_{E+E}(n)^2 = 2|E|^2 - |E| + 2 \sum_n \left(\binom{r_{E+E}(n)}{2} - \left\lfloor \frac{r_{E+E}(n)}{2} \right\rfloor \right);$$

and that the sum counts twice the number of representations $k_1^2 + k_2^2 = k_3^2 + k_4^2$ with $N \leq k_1, k_2, k_3, k_4 \leq N + \Delta$ and $\{k_1, k_2\} \neq \{k_3, k_4\}$. Let $a + ib = \gcd(k_1 + ik_2, k_3 + ik_4)$ and so $k_1 + ik_2 = (a + ib)(x - iy)$ with $k_3 + ik_4 = (a + ib)(x + iy)u$ for some integers a, b, x, y where $u = 1, -1, i$ or $-i$ is a unit. Therefore $k_1 = ax + by, k_2 = bx - ay$, and the four values of u lead to the four possibilities $\{k_3, k_4\} = \{\pm(bx + ay), \pm(ax - by)\}$. All four cases work much the same so just consider $k_3 = bx + ay, k_4 = ax - by$. Then $N \leq ax = (k_1 + k_4)/2$, $bx = (k_3 + k_2)/2 \leq N + \Delta$ and $|by| = |k_1 - k_4|/2$, $|ay| = |k_3 - k_2|/2 \leq \Delta/2$. Multiplying through a, b, x, y by -1 if necessary, we may assume $a > 0$. Therefore $1 + \Delta/N \geq b/a \geq (1 + \Delta/N)^{-1}$ so that

$$b = a + O(a\Delta/N), \quad N/a \leq x \leq N/a + \Delta/a, \quad |y| \leq \Delta/2a.$$

We may assume that $a < \Delta$ else $y = 0$ in which case $\{k_1, k_2\} \neq \{k_3, k_4\}$. Therefore, for a given a the number of possibilities for b, x and y is $\ll (a\Delta/N)(\Delta/a)^2 = \Delta^3/aN$. Summing up over all $a, 1 \leq a \leq \Delta$, gives that $\|f\|_4 \ll \Delta^3(\log \Delta)/N$.

On the other hand if integers a, b, x, y satisfy

$$a \in [7N/\Delta, \Delta/2], \quad b \in [a(1 - \Delta/7N), a], \quad ax \in [N + \Delta/2, N + 2\Delta/3], \quad ay \in [1, \Delta/3],$$

then $N \leq k_1 = ax + by < k_2 = bx - ay, k_3 = bx + ay < k_4 = ax - by \leq N + \Delta$ for $\Delta \leq N/3$, and so $\|f\|_4 \gg \Delta^2 + \Delta^3(\log(\Delta^2/N))/N$.

Conjecture 18. *The exists η such that for any E -polynomial f with $E = \{N^2, \dots, (N + N/(\log N)^\eta)^2\}$, we have*

$$\|f\|_4 \ll \|f\|_2.$$

Conjecture 18 probably holds with $\eta = 1$. If $E = \cup_{i=1}^r E_i$ then we can write any E -polynomial f as $f = \sum_{i=1}^r f_i$, and by the triangle inequality we have $|f|^4 \leq \sum_{i=1}^r |f_i|^4$. Therefore Conjecture 18 implies Bourgain's Conjecture 16 with $\delta = \eta/2$.

In [15] the following weaker conjecture was posed.

Conjecture 19. For any $\alpha < 1$, for any trigonometric polynomial f with frequencies in the set $\{N^2, \dots, (N + N^\alpha)^2\}$, we have

$$\|f\|_4 \ll_\alpha \|f\|_2.$$

Conjecture 19 is trivial for $\alpha \leq 1/2$, yet is completely open for any $\alpha > 1/2$. From (6.1) we immediately deduce:

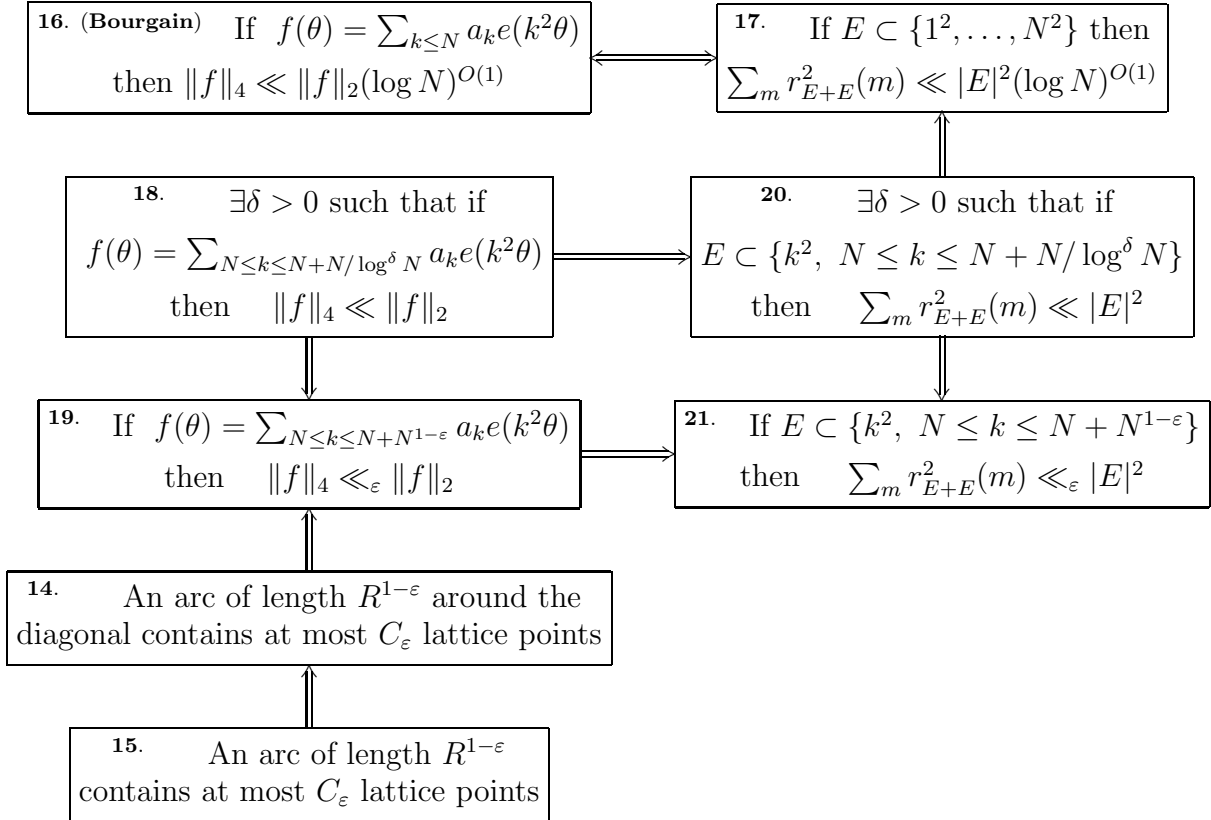
Theorem 18. Conjecture 13 implies Conjecture 19.

The next conjectures 20 and 21 correspond to conjectures 18 and 19, respectively, in the particular case $f(\theta) = \sum_{k^2 \in E} e(k^2\theta)$ and are also open.

Conjecture 20. There exists $\delta > 0$ such that if $E \subset \{k^2, N \leq k \leq N + N/\log^\delta N\}$ then $\sum_m r_{E+E}^2(m) \ll |E|^2$.

Conjecture 21. If $E \subset \{k^2, N \leq k \leq N + N^{1-\varepsilon}\}$ then $\sum_m r_{E+E}^2(m) \ll_\varepsilon |E|^2$.

We now give a flowchart describing the relationships between the conjectures in the second half of the paper.



7. SIDON SETS OF SQUARES

A set of integers A is called a Sidon set if we have $\{a, b\} = \{c, d\}$ whenever $a+b = c+d$ with $a, b, c, d \in A$. More generally A is a $B_2[g]$ -set if there are $\leq g$ solutions to $n = a+b$ with $a, b \in A$, for all integers n (so that a Sidon set is a $B_2[1]$ -set). The set of squares is not a Sidon set, nor a $B_2[g]$ -set for any g ; however it is close enough to have inspired Rudin in his seminal article [27], as well as several sections of this paper.

One question is to find the largest Sidon set $A \subset \{1^2, \dots, N^2\}$. Evidently $A = \{(N - \lfloor \sqrt{N} \rfloor + k)^2, k = 0, \dots, \lfloor \sqrt{N} \rfloor - 1\}$ is a Sidon set of size $\lfloor \sqrt{N} \rfloor$. Alon and Erdős [1] used the probabilistic method to obtain a Sidon set $A \subset \{1^2, \dots, N^2\}$ with $|A| \gg_\varepsilon N^{2/3-\varepsilon}$ (and Lefmann and Thiele [24] improved this to $|A| \gg_\varepsilon N^{2/3}$).

We “measure” the size of infinite Sidon sets $\{a_k\}$ by giving an upper bound for a_k . Erdős and Renyi [20] proved that there exists an infinite $B_2[g]$ -set $\{a_k\}$ with $a_k \ll k^{2+\frac{2}{g}+o(1)}$, for any g . In [12], the first author showed that one may take all the a_k to be squares; and in [13] he showed that there exists an infinite $B_2[g]$ -set $\{a_k\}$ with $a_k \ll k^{2+\frac{1}{g}}(\log k)^{\frac{1}{g}+o(1)}$. Here we adapt this latter approach to the set of squares.

Theorem 19. *For any positive integer g there exists an infinite $B_2[g]$ sequence of squares $\{a_k\}$ such that*

$$a_k \ll k^{2+\frac{1}{g}}(\log k)^{O_g(1)}$$

Proof: Let X_1, X_2, \dots be an infinite sequence of independent random variables, each of which take values 0 or 1, where

$$p_b := \mathbf{P}(X_b = 1) = \frac{1}{b^{\frac{1}{2g+1}}(\log(2+b))^{\beta_g}}.$$

where $\beta_g > 1$ is a number we will choose later. For each selection of random variables we construct a set of integers $\mathcal{B} = \{b \geq 1 : X_b = 1\} = \{b_1 < b_2 < \dots\}$. By the central limit theorem we have $\mathcal{B}(x) \sim c x^{1-\frac{1}{2g+1}}/(\log x)^{\beta_g}$ with probability 1 or, equivalently, $b_k \sim c' (k(\log k)^{\beta_g})^{1+\frac{1}{2g}}$.

We will remove from our sequence of integers \mathcal{B} any integer b_0 such that there exists n for which there are $g+1$ distinct representations of n as the sum of two squares of elements of \mathcal{B} , in which b_0 is the very largest element of \mathcal{B} involved. Let $\mathcal{D} \subset \mathcal{B}$ denote the set of such integers b_0 . Then the set $\{c^2 : c \in \mathcal{B} \setminus \mathcal{D}\}$ is the desired $B_2[g]$ sequence of squares.

Now, if $b_0 \in \mathcal{D}$ then, by definition, there exists $b'_0, b_1, b'_1, \dots, b_g, b'_g \in \mathcal{B}$ with $b'_g \leq b_g < \dots < b_1 < b_0$, for which

$$n = b_0^2 + b'^2_0 = b_1^2 + b'^2_1 = \dots = b_g^2 + b'^2_g.$$

Define $R(n) = \{(b, b'), b \geq b', b^2 + b'^2 = n\}$, and $r(n) = |R(n)|$. Then the probability that $b_0 \in \mathcal{D}$ because of this particular value of n is

$$\mathbf{E}(X_{b_0} X_{b'_0} \sum_{\substack{(b_1, b'_1), \dots, (b_g, b'_g) \in R(b_0^2 + b'^2_0) \\ b_g < \dots < b_1 < b_0}} X_{b_1} X_{b'_1} \dots X_{b_g} X_{b'_g}).$$

The b_j, b'_j are all distinct except in the special case that $n = 2b_g^2$ with $b_g = b'_g$. Thus, other than in this special case, $\mathbf{E}(X_{b_0} X_{b'_0} X_{b_1} X_{b'_1} \dots X_{b_g} X_{b'_g}) = \prod_{j=0}^g p_{b_j} p_{b'_j} \leq (p_{b_0} p_{b'_0})^{g+1}$, since $p_{b_j} p_{b'_j} \leq p_{b_0} p_{b'_0}$ for all j . This gives a contribution above of $\leq (p_{b_0} p_{b'_0})^{g+1} \binom{r(n)-1}{g}$. The terms with $n = 2b_g^2$ similarly contribute $\leq (p_{b_0} p_{b'_0})^{g+1/2} \binom{r(n)-2}{g-1} \leq p_{b_0}^{2g+1} r(n)^{g-1} \ll r(n)^{g-1}/b'_0$. Therefore

$$\mathbf{E}(\mathcal{D}(x) - \mathcal{D}(x/2)) \ll \sum_{\substack{b'_0 \leq b_0 \\ x/2 < b_0 \leq x}} (p_{b_0} p_{b'_0})^{g+1} r(b_0^2 + b'^2_0)^g + \sum_{\substack{b'_0 < b < b_0 \leq x \\ b'^2_0 + b^2 = 2b^2}} \frac{1}{b'_0} r(2b^2)^{g-1}.$$

For the second sum note that $r(m) \ll m^{o(1)}$ and that for any n (and in particular for $n = b_0^2$) we have $\#\{(y, z), n = 2z^2 - y^2, y, z \leq x\} \ll (nx)^{o(1)}$, and so its total contribution is $\ll x^{o(1)} \sum_{b'_0 \leq x} 1/b_0 = x^{o(1)}$.

For the first term we apply Hölder's inequality with $p = 2 - \frac{1}{g+1}$ and $q = 2 + \frac{1}{g}$ to obtain

$$\leq \left(\sum_{\substack{b'_0 \leq b_0 \\ x/2 < b_0 \leq x}} (p_{b_0} p_{b'_0})^{2g+1} \right)^{\frac{g+1}{2g+1}} \left(\sum_{b'_0 \leq b_0 \leq x} r^{2g+1}(b_0^2 + b'^2_0) \right)^{\frac{g}{2g+1}}.$$

As $\beta_g > 1$, we have

$$\sum_{\substack{b'_0 \leq b_0 \\ x/2 < b_0 \leq x}} (p_{b_0} p_{b'_0})^{2g+1} \ll \sum_{x/2 < b_0 \leq x} \frac{1}{b_0 (\log b_0)^{\beta_g(2g+1)}} \sum_{b'_0 \leq b_0} \frac{1}{b'_0 (\log b'_0)^{\beta_g(2g+1)}} \\ \ll \frac{1}{(\log x)^{\beta_g(2g+1)}},$$

$$\text{and } \sum_{b'_0 \leq b_0 \leq x} r^{2g+1}(b_0^2 + b'^2_0) \leq \sum_{n \leq 2x^2} r^{2g+2}(n) \ll x^2 (\log x)^{2^{2g+1}-1},$$

so that

$$\mathbf{E}(\mathcal{D}(x) - \mathcal{D}(x/2)) \ll x^{\frac{2g}{2g+1}} (\log x)^{e_g} \quad \text{where } e_g := g \left(\frac{2^{2g+1} - 1}{2g + 1} \right) - \beta_g(g + 1).$$

Markov inequality's tells us that $\mathbf{P}(\mathcal{D}(2^j) \geq j^2 \mathbf{E}(\mathcal{D}(2^j) - \mathcal{D}(2^{j-1}))) \leq 1/j^2$ so that $\sum_{j \geq 1} \mathbf{P}(\mathcal{D}(2^j) - \mathcal{D}(2^{j-1}) \gg j^{2+e_g} (2^j)^{\frac{2g}{2g+1}}) < \infty$. The Borel-Cantelli lemma then implies that

$$\mathcal{D}(2^j) - \mathcal{D}(2^{j-1}) \ll j^{2+e_g} (2^j)^{\frac{2g}{2g+1}} = o(\mathcal{B}(2^j) - \mathcal{B}(2^{j-1}))$$

with probability 1, provided $\beta_g > \frac{2^{2g+1}-1}{2g+1} + \frac{2}{g}$. Thus there exists a $B_2[g]$ -sequence of the form $\mathcal{A} := \{b^2 : b \in \mathcal{B} \setminus \mathcal{D}\} = \{a_k\}$, where $a_k \ll k^{2+\frac{1}{g}} (\log k)^{\beta_g(2+\frac{1}{g})}$.

Corollary 2. *There exists an infinite Sidon sequence of squares $\{a_k\}$ with $a_k \ll k^3 (\log k)^{12}$.*

Proof: Take $g = 1$ and $\beta = 4$ in the proof above. A more carefully analysis would allow to put $10 + o(1)$ instead of 12.

8. GENERALIZED ARITHMETIC PROGRESSIONS OF SQUARES

A generalized arithmetic progression (GAP) is a set of numbers of the form $\{x_0 + \sum_{i=1}^d j_i x_i : 0 \leq j_i \leq J_i - 1\}$ for some integers J_1, J_2, \dots, J_d and each $x_i \neq 0$. We have seen that many questions in this article are closely related to GAPs of squares of integers and, at the beginning we noted that Fermat proved there are no arithmetic progressions of squares of length 4, and so we may assume each $J_d \leq 3$. We also saw Solymosi's conjecture 6 which claims that there are no GAPs of squares with each $J_i = 2$ and d sufficiently large. This leaves us with only a few cases left to examine:

We begin by examining arithmetic progressions of length 3 of squares: If x^2, y^2, z^2 are in arithmetic progression then they satisfy the Diophantine equation $x^2 + z^2 = 2y^2$. All integer solutions to this equation can be parameterized as

$$x = r(t^2 - 2t - 1), \quad y = r(t^2 + 1), \quad z = r(t^2 + 2t - 1), \quad \text{where } t \in \mathbb{Q} \text{ and } r \in \mathbb{Z}.$$

Therefore the common difference Δ of this arithmetic progression is given by $\Delta = z^2 - y^2 = 4r^2(t^3 - t)$. Integers which are a square multiple of numbers of the form $t^3 - t$, $t \in \mathbb{Q}$ are known as *congruent numbers* and have a rich, beautiful history in arithmetic geometry (see Koblitz's delightful book [22]). They appear naturally when we study right-angled triangles whose sides are rationals because these triangles can be parameterized as $s(t^2 - 1), 2st, s(t^2 + 1)$ with $s, t \in \mathbb{Q}$, and so have area $s^2(t^3 - t)$ (there is a direct correspondence here since we may take the right-angled triangle to have sides $x + z, z - x, 2y$ which has area $z^2 - x^2 = 2\Delta$). It is a highly non-trivial problem to classify the congruent numbers; indeed this is one of the basic questions of modern arithmetic geometry, see [22].

So can we have a 2-by-3 GAP? This would require having two different ways to obtain the same congruent number. The theory of elliptic curves tells us exactly how to do this: We begin with the *elliptic curve*

$$(8.1) \quad E_\Delta : \Delta Y^2 = X^3 - X$$

and the 3-term arithmetic progressions of rational squares are in 1-to-1 correspondence with the rational points $(t, 1/2r)$ on (8.1). Now the rational points on an elliptic curve form an abelian group and so if $P = (t, 1/2r)$ is a rational point on E_Δ then there are rational points $2P, 3P, \dots$. This is all explained in detail in [22]. All we need is to note that $2P = (T, 1/2R)$ where

$$T = \frac{(t^2 + 1)^2}{4(t^3 - t)} = \frac{y^2}{\Delta} \quad \text{and} \quad R = \frac{8r(t^3 - t)^2}{(t^2 + 1)(t^2 + 2t - 1)(t^2 - 2t - 1)} = \frac{\Delta^2}{2xyz}.$$

So we have infinitely many 2-by-3 GAPs of squares where the common difference of the 3-term arithmetic progressions is Δ , for any congruent number Δ .

How about 3-by-3 GAPs of squares? Let us suppose that the common difference in one direction is Δ ; having a 3-by-3 GAP is then equivalent to having y_1^2, y_2^2, y_3^2 in arithmetic progression. But note that $y_i^2 = \Delta T_i = \Delta x(2P_i)$ (where $x(Q)$ denotes the x -coordinate of Q on a given elliptic curve). Therefore 3-by-3 GAPs of squares are in 1-to-1 correspondence with the sets of congruent numbers and triples of rational points, $(\Delta; P_1, P_2, P_3) : P_1, P_2, P_3 \in E_\Delta(\mathbb{Q})$ for which the x -coordinates $x(2P_1), x(2P_2), x(2P_3)$ are in arithmetic progression (other than the triples $-1, 0, 1$ which do not correspond to squares of interest).

In [8] it is proved that if there is such an arithmetic progression of rational points then the *rank* of E_Δ must be at least 2; that is there are at least two points of infinite order in the group of points that are independent. Bremner became interested in the same issue from a seemingly quite different motivation:

A 3-by-3 *magic square* is a 3-by-3 array of numbers where each row, column and diagonal has the same sum. Solving the linear equations that arise it may be parameterized as

$$\begin{pmatrix} u + v & u - v - \Delta & u + \Delta \\ u - v + \Delta & u & u + v - \Delta \\ u - \Delta & u + v + \Delta & u - v \end{pmatrix}$$

The entries of the magic square form the 3-by-3 GAP $\{(u - v - \Delta) + j_1 v + j_2 \Delta : 0 \leq j_1, j_2 \leq 2\}$. Hence the question of finding a non-trivial 3-by-3 magic square with entries from a given set E is *equivalent* to the question of finding a non-trivial 3-by-3 GAP with entries from a given set E ; in particular when E is the set of squares. (This connection is beautifully explained in [26].)

We believe that the existence of non-trivial 3-by-3 GAPs of squares, and equivalently of non-trivial 3-by-3 magic squares of squares, remain open.

9. THE abc -CONJECTURE

In [4] it was shown that the large sieve implies that if there are $\gg \sqrt{k} \log k$ squares amongst $a + b, a + 2b, \dots, a + kb$ then $b \geq e^{\sqrt{k}}$. We wish to obtain an upper bound on b also. We shall do so assuming one of the most important conjectures of arithmetic geometry:

Conjecture 22. (The abc -conjecture) *If $a + b = c$ where a, b and c are coprime positive integers then $r(abc) \gg c^{1-o(1)}$ where $r(abc)$ is the product of the distinct primes dividing abc .*

Unconditional results on the abc -conjecture are from this objective, giving only that $r(abc) \gg (\log c)^{3-o(1)}$, for some $A > 0$ (see [29]). Nonetheless, by considering the strongest feasible version of certain results on linear forms of logarithms, Baker [2] made a conjecture which implies the stronger

$$(9.1) \quad r(abc) \gg c / \exp((\log c)^\tau),$$

with $\tau = 1/2 + o(1)$.

Lemma 1. *Suppose that $A + t_j B$ is a square for $j = 1, 2, 3, 4, 5$, where A, B and the t_j are integers and $(A, B) = 1$. Let $T = \max_j |t_j|$. Then (9.1) implies that $A + B \ll \exp(O(T^{9\tau/(1-\tau)}))$. Moreover if $B \gg A^{5/6-\varepsilon}$ then we may improve this to $B \ll \exp(O(T^{6\tau/(1-\tau)}))$.*

Proof: There is always a partial fraction decomposition

$$\frac{1}{\prod_{j=1}^5 (x + t_j)} = \sum_{j=1}^5 \frac{e_j}{x + t_j} \quad \text{where} \quad e_j = \frac{1}{\prod_{i=1, i \neq j}^5 (t_i - t_j)},$$

so that $\sum_j e_j t_j^\ell = 0$ for $0 \leq \ell \leq 3$. Let L be the smallest integer such that each $E_j := L e_j$ is an integer. Define the polynomials

$$h(x) := \prod_{\substack{1 \leq j \leq 5 \\ E_j > 0}} (x + t_j)^{E_j} \quad \text{and} \quad g(x) := \prod_{\substack{1 \leq j \leq 5 \\ E_j < 0}} (x + t_j)^{-E_j}, \quad \text{with} \quad f(x) := h(x) - g(x).$$

If $h(x)$ has degree D then the coefficient of x^{D-i} in $f(x)$ is a polynomial in the $\sum_j e_j t_j^\ell$ with $0 \leq \ell \leq i$, so we deduce that $f(x)$ has degree $D - 4$. Now let $a = B^D h(A/B)$, $b = B^D g(A/B)$, $c = B^4 \cdot B^{D-4} f(A/B)$ and then $a' = a/(a, b)$, $b' = b/(a, b)$, $c' = c/(a, b)$. Thus $r(a'b'c') \leq r(\prod_{j=1}^5 (A + t_j B)) |B| |c'| / B^4 \leq \prod_{j=1}^5 (A + t_j B)^{1/2} |c'| / B^3$. Now $\prod_{j=1}^5 (A + t_j B) \ll B^{6-2\varepsilon}$ provided $T = B^{o(1)}$ and $A \ll B^{6/5-\varepsilon}$, in which case $r(a'b'c') \ll |c'| / B^\varepsilon$. Then, by (9.1), we have $(\log c)^\tau \gg \log B$. Now $c = a + b \ll (A + TB)^D$ so that

$\log c \ll D \log B$; we deduce that $B \ll \exp(O(D^{\tau/(1-\tau)}))$. Finally note that $D \ll \max_{\ell} |E_{\ell}| \leq \prod_{1 \leq i < j \leq 5, i, j \neq \ell} |t_i - t_j| \ll T^6$, and the second result follows.

In case that $A \gg B^{6/5-\varepsilon}$ we may replace t_j by $1/t_j$ in our construction of polynomials given above. In that case we get new exponents $e_j^* = e_j t_j^3 \prod_{i=1}^5 t_i$ and therefore $|E_j^*| \leq |t_j|^3 |E_j|$. We now have integers $a^* = \kappa A^d h^*(\frac{B}{A})$, $b^* = \kappa A^d g^*(\frac{B}{A})$, $c^* = \kappa A^4 \cdot A^{d-4} f^*(\frac{B}{A})$ where $\kappa := \prod_j t_j^{|E_j^*|}$ and d is the degree of h^* . Thus we have that either $A \ll T^{O(1)}$ or $A \ll \exp(O(d^{\tau/(1-\tau)}))$ and $d \ll T^9$.

We can apply this directly: If there are $\gg \sqrt{k}$ squares amongst $a+b, a+2b, \dots, a+kb$ then there must be $i_1 < \dots < i_5$ with $i_5 < i_1 + O(\sqrt{k})$ such that each $a+i_j b$ is a square. Thus by Lemma 1 with $A = a+i_1 b$, $B = b$, $t_j = i_j - i_1$, assuming (9.1) with Baker's $\tau = 1/2 + o(1)$, we obtain $a+b \ll \exp(k^{9/2+o(1)})$. Therefore we may, in future, restrict our attention to the case $k^{1/2} \ll \log(a+b) \ll k^{9/2+o(1)}$.

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