

A second note on Fermat's conjecture.

To Professor László Kalmár on his 50th birthday.

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1. In a previous note¹⁾ one of us proposed the following problem. Let q be a fixed odd prime and we consider $R_q(N)$ the number of integer (x, y, z) -solutions of the equation

$$(1.1) \quad x^q + y^q = z^q$$

with

$$(1.2) \quad 1 \leq x, y, z \leq N$$

and

$$(1.3) \quad (x, y) = (x, z) = (y, z) = 1.$$

If Fermat's conjecture is true, then $R_q(N) = 0$; the proposed problem consists in finding *upper estimations* for $R_q(N)$. The number of systems with (1.2) is N^3 ; the first non-trivial estimation in¹⁾ was

$$(1.4) \quad R_q(N) < c_1 N \log^{\frac{1}{q-1}} N,$$

where c_1 depends only upon q . In this note we give two more upper estimations; we shall show by elementary means the better estimation

$$(1.5) \quad R_q(N) < q \left(1 + 3.2^{\frac{1}{q}}\right) N^{\frac{2}{q}},$$

and afterwards, using deeper tools, the estimation

$$(1.6) \quad R_q(N) < c_2(q) \frac{N^{\frac{2}{q}}}{\log^{2-\frac{2}{q}} N}.$$

It is very probable that to prove the inequality

$$(1.7) \quad R_q(N) < c_3 N^{\frac{1}{q}}$$

¹⁾ P. TURÁN, A note on Fermat's conjecture. *J. Indian Math. Soc.*, **15**. (Part A), (1951), 47—50. — Here as well as in the quoted paper solutions (a, b, c) and (b, a, c) with $a \neq b$ are always counted as distinct ones.

is within the possibilities; concerning that see **6**. A proof of

$$(1.8) \quad R_q(N) < c_4(\varepsilon) N^\varepsilon$$

for arbitrarily small positive ε seems to be however very deep.

2. We denote by $R'_q(N)$ the number of solutions of (1.1) satisfying the additional condition

$$(2.1) \quad (x, q) = (y, q) = (z, q) = 1.$$

Let us consider first $R'_q(N)$. We write

$$(2.2) \quad (z-x) \frac{z^q - x^q}{z-x} = y^q.$$

We suppose p to be a prime, $p \neq q$ and

$$(2.3) \quad p \mid (z-x),$$

moreover

$$(2.4) \quad p \mid \left(\frac{z^q - x^q}{z-x} \right).$$

From (2.3) and (2.4) we obtain

$$0 \equiv \frac{z^q - x^q}{z-x} \equiv qz^{q-1} \pmod{p},$$

i. e. $p \mid z$. But (2.3) gives then $p \mid x$, i. e. $(x, z) > 1$, a contradiction to (1.3).

Thus the greatest common divisor of $(z-x)$ and $\frac{z^q - x^q}{z-x}$ could only be q ; but from (2.2) this would mean $q \mid y$ which contradicts to (2.1). This means that

$$\left(z-x, \frac{z^q - x^q}{z-x} \right) = 1,$$

i. e. with a positive integer a

$$(2.5) \quad z-x = a^q.$$

What an upper limitation can be given for a ? From (2.5) and (1.2) we get

$$a^q < z \leq N,$$

i. e.

$$(1.6) \quad a < N^{\frac{1}{q}}.$$

A similar reasoning gives also

$$\left(z-y, \frac{z^q - y^q}{z-y} \right) = 1,$$

i. e. with a positive integer b

$$(2.7) \quad z-y = b^q,$$

$$(2.8) \quad b < N^{\frac{1}{q}}.$$

Thus the values of a and b can be chosen at most on $N^{\frac{2}{q}}$ ways. Fixing such a pair

$$x = z - a^q, \quad y = z - b^q,$$

we get from (1.1)

$$(z - a^q)^q + (z - b^q)^q = z^q.$$

Hence the number of z -values — and at the same time that of the (x, y, z) -solutions — is at most q , i. e.

$$(2.9) \quad R'_q(N) < q N^{\frac{2}{q}}.$$

3. Next we consider $R''_q(N)$, the number of the solutions of (1.1) with

$$(3.1) \quad q | xyz.$$

(1.3) gives that only one of x, y, z is divisible by q ; suppose $q | x$. Then

$$(y, q) = (z, q) = 1$$

and writing the equation (1.1) in the forms

$$(z - x) \frac{z^q - x^q}{z - x} = y^q,$$

$$(x + y) \frac{x^q + y^q}{x + y} = z^q,$$

the reasoning of **2.** can be repeated. Thus with positive integer a and b we get

$$z - x = a^q,$$

$$x + y = b^q$$

and

$$\begin{aligned} a^q < z \leq N, & \quad a < N^{\frac{1}{q}}, \\ b^q \leq 2N, & \quad b \leq (2N)^{\frac{1}{q}}. \end{aligned}$$

Hence the contribution of the solutions with $q | x$ is

$$< q(2N^2)^{\frac{1}{q}},$$

i. e.

$$(3.2) \quad R''_q(N) < 3q \cdot 2^{\frac{1}{q}} \cdot N^{\frac{2}{q}}.$$

(2.9) and (3.2) prove the inequality (1.5).

4. The proof of (1.6) is deeper. It is based on the following theorem of Furtwängler²⁾. For every (x, y, z) -solution of the equation (1.1) with (1.3)

²⁾ P. FURTWÄNGLER, Letzter Fermat'scher Satz und Eisensteinsches Reciprocitäts-gesetz. *Sitzungsberichte Akad. Wiss. Wien* **121** (1912), p 589—592. — In fact, this is only a special case of what he actually proved.

holds that, if u is one of x, y, z which is not divisible by q , then u is built up exclusively of such p primes for which

$$(4.1) \quad p^{q-1} \equiv 1 \pmod{q^2}.$$

It is easy to see that the p -primes satisfying (4.1) are contained in $(q-1)$ arithmetical progressions mod q^2

$$(4.2) \quad \begin{array}{ccc} p \equiv l_1 \pmod{q^2} & (=1) & \pmod{q^2} \\ \vdots & & \vdots \\ p \equiv l_{q-1} \pmod{q^2} & & \pmod{q^2}. \end{array}$$

Indeed, if m is a primitive root mod q^2 and the p -primes satisfying (4.1) are written in the form

$$p \equiv m^k \pmod{q^2},$$

then

$$m^k(q-1) \equiv 1 \pmod{q^2}$$

and, since m is a primitive root mod q^2 , we get q/k , i. e.

$$k = q, 2q, \dots, (q-1)q.$$

This proves (4.2); we shall use Furtwängler's theorem in this form.

5. We consider again $R'_q(N)$. The a in (2.5) is a divisor of y and thus we know about a not only that $a \leq N^{\frac{1}{q}}$, but, owing to (4.2), since $(y, q) = 1$, that a is composed exclusively of p primes satisfying (4.2). Let $a_1 < a_2 < \dots$ be all positive integers composed of the progressions (4.2). If $s = \sigma + it$ is the complex variable, then we have for $\sigma > 1$

$$(5.1) \quad F(s) = \sum_r \frac{1}{a_r^s} = \prod_{r=1}^{q-1} \prod_{p \equiv l_r \pmod{q^2}} \frac{1}{1 - \frac{1}{p^s}}.$$

Standard theorems in the theory of L -functions of Dirichlet show the existence of functions $f_r(s)$ regular in the domain

$$\sigma > 1 - \frac{1}{\log(2 + |t|)}$$

and satisfying here an inequality

$$|f_r(s)| \leq \exp \left\{ c_5(\varepsilon, q) \frac{\log(3 + |t|)}{\log \log(3 + |t|)} \right\}$$

such that

$$\begin{aligned} F(s) &= f_1(s) \exp \left\{ \sum_{r=1}^{q-1} \sum_{p \equiv l_r \pmod{q^2}} \frac{1}{p^s} \right\} = \\ &= f_1(s) \exp \left\{ \sum_{r=1}^{q-1} \frac{1}{q(q-1)} \sum_{\chi \pmod{q^2}} \bar{\chi}(l_r) \log L(s, \chi) \right\} = \\ &= f_2(s) \exp \left\{ \sum_{r=1}^{q-1} \frac{1}{q(q-1)} \log L(s, \chi_0) \right\} = \frac{f_3(s)}{(s-1)^{\frac{1}{q}}}. \end{aligned}$$

A standard technique shows then for $Y \rightarrow \infty$

$$\sum_{a, y \equiv Y} 1 \sim c_6(q) \frac{Y}{\log^{1-\frac{1}{q}} Y}.$$

Hence the number of the possible a -values is (with $Y = N^{\frac{1}{q}}$)

$$< c_7(q) \frac{N^{\frac{1}{q}}}{\log^{1-\frac{1}{q}} N}$$

and thus repeating the reasoning of **2**, we get

$$R'_q(N) < c_8(q) \frac{N^{\frac{2}{q}}}{\log^{2-\frac{2}{q}} N}.$$

A similar change in the reasoning in **3** gives at once

$$R''_q(N) < c_9(q) \frac{N^{\frac{2}{q}}}{\log^{2-\frac{2}{q}} N},$$

which proves (1.6).

6. We return to (2.5). Fixing the value of a we get from (1.1)

$$(6.1) \quad x^q + y^q = (x + a^q)^q.$$

Denoting the number of the positive integer solutions of (6.1) with $x, y \leq N$ by $f(N, a)$ we get

$$(6.2) \quad R'_q(N) < \sum_{a < N^{1/q}} f(N, a).$$

If one could show that the number of solution of (6.1) is $O(N^\epsilon)$ then (6.2) would give at once

$$R'_q(N) < c_{10}(q, \epsilon) N^{\frac{1}{q} + \epsilon}$$

and slight changes would result also $R_q(N) < c_{11}(q, \epsilon) N^{\frac{1}{q} + \epsilon}$.

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