SOME REMARKS ON THE abc-CONJECTURE

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ABSTRACT. Let $r(x)$ be the product of all distinct primes dividing a nonzero integer $x$. The abc-conjecture says that if $a, b, c$ are nonzero relatively prime integers such that $a + b + c = 0$, then the biggest limit point of the numbers

$$\log \frac{\max(\{|a|, |b|, |c|\})}{\log r(abc)}$$

equals 1. We show that in a natural anologue of this conjecture for $n \geq 3$ integers, the largest limit point should be replaced by at least $2n - 5$. We present an algorithm leading to numerous examples of triples $a, b, c$ for which the above quotients strongly deviate from the conjectural value 1.

1. INTRODUCTION

Let $a, b, c$ be nonzero integers such that

$$a + b + c = 0 \quad \text{and} \quad \gcd(a, b, c) = 1,$$

and let $r(abc)$ be the product of distinct prime numbers dividing $abc$. J. Oesterlé posed the question whether the numbers

$$(1) \quad L = L(a, b, c) = \frac{\log \max(\{|a|, |b|, |c|\})}{\log r(abc)}$$

are bounded. This question was refined by D. W. Masser who conjectured that for each $\epsilon > 0$ there exists a positive constant $C(\epsilon)$ such that

$$\max(\{|a|, |b|, |c|\}) \leq C(\epsilon) r(abc)^{1+\epsilon}.$$  

This is the abc-conjecture. It is easy to see that the abc-conjecture is equivalent to the inequality

$$\lim \sup \{L\} \leq 1,$$

where $\lim \sup \{L\}$ denotes the largest limit point of the quotients (1). But it is not difficult to show that there is a limit point of this set which is $\geq 1$. Thus the abc-conjecture can be formulated as the equality

$$\lim \sup \{L\} = 1.$$  

The first purpose of the present note is to comment on a rather evident generalization of the abc-conjecture to a statement involving $n \geq 3$ integers. We show that 1 in the above equality should be replaced by at least $2n - 5$. This
number is also our conjectural value in the \textquotedblleft n-conjecture\textquotedblright. The second objective of the paper is to present some numerical results concerning deviations of the quotient (1) from the conjectural value 1 in the case of abc-conjecture. Our results do not contradict the conjecture, but the presence of rather big prime factors in the triples \(a, b, c\) leading to quotients \(L\) strongly deviating from 1 makes it somewhat questionable.

2. THE n-CONJECTURE FOR \(Z\)

Let \(a_1, a_2, \ldots, a_n \in \mathbb{Z}\), where \(n \geq 3\), satisfy
\begin{itemize}
  \item[(i)] \(\gcd(a_1, a_2, \ldots, a_n) = 1\),
  \item[(ii)] \(a_1 + a_2 + \cdots + a_n = 0\),
  \item[(iii)] no proper subsum of (ii) is equal to 0.
\end{itemize}

Denote
\begin{equation}
M_n = M = \max_{1 \leq j \leq n} (|a_j|), \quad m_n = m = r(a_1 \cdots a_n), \quad L_n = L(a_1, \ldots, a_n) = \log M_n / \log m_n.
\end{equation}

The \(n\)-conjecture asserts that, for given \(n \geq 3\),
\begin{itemize}
  \item[1.] the numbers \(L_n\) are bounded,
  \item[2.] \(\lim \sup \{L_n\} = 2n - 5\),
\end{itemize}
where \(L_n\) runs over numbers (2) corresponding to all \(n\)-tuples of integers satisfying (i)-(iii).

**Theorem 1.** For every \(n \geq 3\),
\[\lim \sup \{L_n\} \geq 2n - 5.\]

First we prove a lemma.

**Lemma 1.** For every \(k \geq 0\), there exists a polynomial \(f_k \in \mathbb{Z}[x]\) of degree \(k\) with positive coefficients such that
\begin{equation}
\frac{x^{2k+1} - 1}{x - 1} = x^k f_k \left( \left( \frac{x - 1}{x} \right)^2 \right).
\end{equation}

**Proof.** For \(\alpha_j = 2\pi j / (2k + 1), \quad j = 1, 2, \ldots, k\), we have
\[\frac{x^{2k+1} - 1}{x - 1} = \prod_{j=1}^{k} (x^2 - 2x \cos \alpha_j + 1) = x^k \prod_{j=1}^{k} \left( \frac{(x - 1)^2}{x} + 2(1 - \cos \alpha_j) \right).\]

It is sufficient to take
\[f_k(z) = \prod_{j=1}^{k} (z + 2(1 - \cos \alpha_j)).\]

From (3) it follows that \(f_k\) has integral coefficients, and since all its roots are negative, all its coefficients are positive. \(\Box\)
Remark 1. One can also define the polynomial $f_k(z)$ explicitly:

$$f_k(z) = \sum_{j=0}^{k} \frac{2k+1}{k+j+1} \binom{k+j+1}{2j+1} z^j,$$

or inductively:

$$f_0(z) = 1, \quad f_1(z) = z + 3,$$

and, for $k \geq 1$,

$$f_{k+1}(z) = (z+2)f_k(z) - f_{k-1}(z).$$

Using (4) or (5), one can continue the list:

$$f_2(z) = z^2 + 5z + 5,$$
$$f_3(z) = z^3 + 7z^2 + 14z + 7,$$
$$f_4(z) = z^4 + 9z^3 + 27z^2 + 30z + 9,$$
$$f_5(z) = z^5 + 11z^4 + 44z^3 + 77z^2 + 55z + 11,$$
$$f_6(z) = z^6 + 13z^5 + 65z^4 + 156z^3 + 182z^2 + 91z + 13.$$

As in Lemma 1, one can prove the existence of polynomials $g_k \in \mathbb{Z}[x]$ of degree $k$ with positive coefficients such that

$$\frac{x^{2k+2} - 1}{x^2 - 1} = x^k g_k \left( \frac{(x-1)^2}{x} \right)$$

for $k \geq 0$. These polynomials can be defined by a formula similar to (4):

$$(4') \quad g_k(z) = \sum_{j=0}^{k} \binom{k+j+1}{2j+1} z^j,$$

or inductively by

$$g_0(z) = 1, \quad g_1(z) = z + 2,$$

and, for $k \geq 1$,

$$(5') \quad g_{k+1}(z) = (z+2)g_k(z) - g_{k-1}(z).$$

Let us note that the same arguments as in the proof of Lemma 1 give, for $n > 2$,

$$\Phi_n(x) = x^{\phi(n)/2} p_n \left( \frac{(x-1)^2}{x} \right),$$

where $\Phi_n$ is the $n$th cyclotomic polynomial, and $p_n \in \mathbb{Z}[x]$ has positive coefficients and degree $\phi(n)/2$ ($\phi(n)$ is the Euler totient function). The splitting field of $p_n$ is the maximal real subfield of the splitting field of $\Phi_n$ over the rational numbers. Defining $p_1(x) = p_2(x) = 1$, one can easily prove that $f_k$ and $g_k$ are the products of all polynomials $p_d$ for $d$ dividing $2k+1$, respectively, $2k+2$.

Proof of Theorem 1. Let

$$(6) \quad f_k(z) = \sum_{j=0}^{k} s_j z^j,$$
where according to Lemma 1, the \( s_j \) are positive integers. If in (3) we put \( k = n - 3 \) and \( x = -a_1/a_2 \), then, in view of (6), we get

\[
\begin{align*}
    a_1^{2n-5} + a_2^{2n-5} - \sum_{j=0}^{n-3} s_j (a_1 + a_2)^{2j+1} (-a_1 a_2)^{n-j-3} &= 0.
\end{align*}
\]

If we choose \( a_1 = 2^i \), where \( i > 1 \), and \( a_2 = -1 \), then we have a sum of \( n \) summands equal to zero, with no proper subsum equal to zero, since only the first summand is positive. The second summand is \(-1\), hence the gcd of all summands is \( 1 \). Therefore the conditions (i)–(iii) of the \( n \)-conjecture are satisfied. With this choice of \( a_1 \) and \( a_2 \), we have from (7),

\[
M_n = 2^{i(2n-5)}.
\]

Consequently, denoting \( c = 2s_0 s_1 \cdots s_{n-3} \) and taking the logarithms to the base 2, we get

\[
L_n = \frac{i(2n-5)}{\log r((2^i - 1)c)} \geq \frac{i(2n-5)}{i + \log r(c)} \rightarrow 2n - 5
\]

for \( i \to \infty \). Since there are infinitely many \( i \) such that the numbers \( 2^i - 1 \) are relatively prime (e.g., all prime \( i \)), it is easy to check that the quotients \( L_n \) corresponding to those \( i \) are different. Therefore, the set \( \{L_n\} \) has an accumulation point equal at least \( 2n - 5 \). \( \square \)

Remark 2. Let \( a_1, a_2, a_3 \) satisfy the assumptions (i)–(iii) for the 3-conjecture with \( a_1 = \max(|a_1|, |a_2|, |a_3|) \) and \( L_3 = L(a_1, a_2, a_3) \). If for some \( n > 3 \), every prime divisor of the coefficients of \( f_{n-3} \) divides \( a_1 a_2 a_3 \), then (7) gives an example for the \( n \)-conjecture with

\[
L_n = (2n-5)L_3,
\]

since \( M_n = a_1^{2n-5} \) and all other terms in (7) are negative.

Thus, the example of E. Reysat for the 3-conjecture

\[
23^5 - 109 \cdot 3^{10} - 2 = 0
\]

with \( L_3 = 1.629912 \) gives the example

\[
23^{15} - 109^3 \cdot 3^{30} - 2^3 - 2 \cdot 3^{11} \cdot 23^5 \cdot 109 = 0
\]

for the 4-conjecture with \( L_4 = 3L_3 = 4.889735 \).

The \( n \)-Conjecture for \( K[t] \)

Let \( K \) be a field of characteristic zero. For a nonzero polynomial \( a \in K[t] \), let \( r(a) \) be the sum of the degrees of all distinct irreducible factors of \( a \) in \( K[t] \). Let \( a_1, a_2, \ldots, a_n \in K[t] \), where \( n \geq 3 \), satisfy \( \max_{1 \leq j \leq n} \deg(a_j) > 0 \) and (i)–(iii) as above. Denote

\[
\begin{align*}
    M_n &= M = \max_{1 \leq j \leq n} \deg(a_j),
    m_n = m = r(a_1 \cdots a_n),
    L_n &= L(a_1, \ldots, a_n) = M_n/m_n.
\end{align*}
\]

The \( n \)-conjecture asserts that for every \( n \geq 3 \),

\[
M_n \leq (2n-5)(m_n - 1).
\]
Theorem 2. For every $n \geq 3$,

$$\limsup\{L_n\} \geq 2n - 5.$$  

Proof. Put in (7) $a_1 = t^r + 1$, where $r > 0$ and $a_2 = -1$. Then

$$\sum_{j=0}^{n-3} s_j t^{2rj}(t^r + 1)^{n-j-3} = 0.$$  

Thus, we have a sum of $n$ summands satisfying the assumptions of the $n$-conjecture. Moreover, for (8), we have

$$M_n = (2n - 5)r, \quad m_n = 1 + r.$$  

Consequently,

$$L_n = \frac{(2n - 5)r}{1 + r} \to 2n - 5$$  

for $r \to \infty$. □

Remark 3. In the case of polynomial rings an estimation from above is known:

$$L_n \leq \binom{n - 1}{2}$$  

(see [1], [7] and [8]). Thus, from Theorem 2, we get

Corollary. If $n = 3$ or 4, then for the ring $K[t]$ we have

$$\limsup\{L_n\} = 2n - 5.$$  

With a suitable modification of the definition of $L_n$, Theorem 2 and its corollary can be extended to algebraic curves of arbitrary genus over fields of characteristic zero (see [1], [7] and [8]).

4. Examples related to the abc-conjecture

The example of E. Reyssat given above can be interpreted as follows. The equality

$$23^5 - 109 \cdot 9^5 = 2, \quad \text{i.e.,} \quad \left(\frac{23}{9}\right)^5 - 109 = \frac{2}{95},$$  

implies that $23/9$ is a good rational approximation to $\sqrt[5]{109}$. Let us consider the continued fraction

$$\sqrt[5]{109} = [2, 1, 1, 4, 77733, \ldots].$$  

The very large term 77733 implies that the convergent $[2, 1, 1, 4]$ gives a very good approximation to $\sqrt[5]{109}$. In fact, we have $[2, 1, 1, 4] = 23/9$.

Starting from this observation, we have made an extended computer search for continued fraction expansions of numbers $\sqrt[5]{k}$. Having a suitable convergent of the continued fraction of $\sqrt[5]{k}$, say, $p/q$, we put $c = \max(kq^n, p^n)$, $b = \min(kq^n, p^n)$, $a = c - b$ (divided by gcd$(a, b, c)$). We have also considered several rational numbers $p/q$ which can be derived from the convergents of continued fractions, and which give good approximations to $\sqrt[5]{k}$ such that $p$ and $q$ have many prime power divisors.

The "obvious" idea was that if $[a_0, a_1, \ldots]$ is the fraction, then one should look for the convergents corresponding to large $a_i$ in order to get a good approximation. Then we looked for large $q$ in the convergents $p/q$ (which is
more reasonable). But it appears that these properties are not relevant in general. For example, the best-known result \( L = 1.629912 \) can be obtained not only from \( \sqrt[3]{109} \) but also from \( \sqrt[3]{2507} = [50, 14, 3, 2, 1, 1, 1, 1, \ldots] \) and the convergent of length 6 equal to \( 23^3/35^3 \).

Using this method, we obtained several new interesting examples (indicated B-B) and all previously known. All results with \( L > 1.4 \) known to us at present (March 15, 1993) are included in the table. It contains the examples given by B.M.M. de Weger in [6] and the examples constructed by A. Nitaj in [3]. We express our thanks to A. Nitaj for sending us his examples, which were obtained by a different method. We have also included one example of Xiao Gang (sent to us by B.M.M. de Weger, see also Oesterlé [4]) and one of J. Kanapka (sent to us by N. Elkies).

### Table (version of March 15, 1993)

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Some words about the program. The examples are constructed with $\sqrt[k]{Q}$, where $2 \leq k \leq 2 \cdot 10^5$, $2 \leq n \leq 15$ (for $k \leq 100$, we choose $n$ up to 20, but the increase of $n$ has not resulted in new examples). The computations were carried out with all convergents up to length 10 (for $k \leq 100$ up to 20 without new examples). In order to limit the computation time, we put the restriction $c < 10^{15}$ (in some intervals for $k$, we took $c < 10^{30}$).

Of course, there is nothing which makes it impossible to continue computations of new examples by using the same method. But it is much more desirable to understand why so many examples with large values of $L$ can be constructed in such a way. The first of the three remarks concluding the paper is closely related to this question.

**Remark 4.** As we noted before, all examples in the table can be obtained by using continued fractions of $\sqrt[k]{Q}$ for suitable $n$ and $k$. In order to check this possibility, let us introduce the following notations. If $x$ is a positive
integer, let \( n(x) \) be the largest exponent of prime numbers dividing \( x \), and for \( s(x) \geq n(x) \), let \( x'_{s(x)} \) be the unique integer such that \( xx'_{s(x)} = r(x)^{s(x)} \). We shall write \( x' \) when \( s(x) \) is clear from the context. With these notations, we have the following easy result:

**Lemma 2.** Let \( a, b, c \) be positive integers such that \( a + b = c \), and \( a = \rho b \), where \( 0 < \rho < 1 \). If

\[
\frac{1}{\rho} < \frac{s(a)}{r(a)} \quad \text{or} \quad \rho < \frac{s(b)}{r(b)} \quad \text{or} \quad \rho < \frac{s(c)}{2r(c)},
\]

then \( r(a) \) is a convergent of \( \frac{a}{\sqrt{a'c}} \), or \( r(b) \) is a convergent of \( \frac{b}{\sqrt{b'c}} \), or \( r(c) \) is a convergent of \( \frac{c}{\sqrt{b'c}} \), respectively.

**Proof.** Consider the third case, that is, \( \rho < \frac{s(c)}{2r(c)} \). Using the mean value theorem, we get

\[
r(c) - \frac{a}{\sqrt{a'c}} \leq \frac{b}{s(c)\sqrt{b'c}} (cc' - bc') \leq \frac{r(c)a}{s(c)b} < \frac{1}{2}.
\]

Thus, \( r(c) \) is a convergent of \( \frac{c}{\sqrt{b'c}} \) (in fact, the second one). Similar arguments show that in the first case (or in the second, with \( a \) replaced by \( b \)), \( \frac{a}{\sqrt{a'c}} - r(a) < 1 \), so \( r(a) \) is the first convergent of \( \frac{a}{\sqrt{a'c}} \). \( \square \)

Using Lemma 2, we can easily check that its assumptions are satisfied for almost all the examples in the table with \( s(x) = n(x) \) for \( x \in \{a, b, c\} \) (in fact for all but five examples with \( x = b \) or \( c \)). In any case, one can choose a sufficiently large value of, say, \( s(c) \), in order to fulfill these assumptions. Then, according to our algorithm, we get all the examples using the roots and their convergents given by the lemma. Of course, such a choice of \( n \) and \( k \) in \( \sqrt{k} \) is not always the optimal one.

**Remark 5.** There are other quotients, similar to (2), which are natural in connection with the \( abc \)-conjecture. Following [4] and [5], we let

\[
L' = L'(a, b, c) = \frac{\log |abc|}{\log r(abc)};
\]

for relatively prime nonzero integers \( a, b, c \) such that \( a + b = c \). It is evident that the \( abc \)-conjecture implies the inequality

\[
\lim \sup \{L'\} \leq 3.
\]

The deviations of the quotients \( L' \) from 3 have been studied intensively by A. Nitaj (see [3]). The biggest value \( L' = 4.419014 \) corresponds to Nitaj’s Example 7 in the table. It is a better result than \( L' = 4.107567 \) corresponding to the example of Xiao Gang cited in [4] (Example 66 in the table).

**Remark 6.** We observe that in all the examples in the table, the exponent of at least one of the prime numbers involved is \( \leq 2 \). If \( x \) is a nonzero integer, we say that \( x \) is \( n \)-powerful if \( p^n \) divides \( x \) for each prime number \( p \) dividing \( x \) (2-powerful numbers are usually called powerful—see, e.g., [2, B16]). With this terminology, we do not have an example of 3-powerful integers \( a, b, c \) such that \( a + b = c \), \( \gcd(a, b, c) = 1 \) and \( L > 1.4 \) (or even with \( L > 1.2 \)). However,

\[
271^3 + 2^3 \cdot 3^5 \cdot 73^3 = 919^3
\]
with not impressive $L$. We do not know whether there are 4-powerful $a, b, c$ such that $a + b = c$ and $\gcd(a, b, c) = 1$. But there are reasons to believe that there are no $n$-powerful integers satisfying these conditions when $n \geq 5$. In fact, our computations strongly suggest that

$$\max(|a|, |b|, |c|) \leq r(abc)^s$$

with $s < 1.65$. If this is true, then for $n$-powerful numbers $a, b, c$, we get $r(abc) \leq \sqrt[3]{|abc|}$. Therefore, $|abc|^n \leq |abc|^{3s} < |abc|^5$, so $n < 5$.

**Bibliography**


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